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RISKS ASSOCIATED WITH THE TRANSPORTATION TO TREATMENT OF HAZARDOUS WASTE SUBSTANCES

PHASE I

Alberta
ENVIRONMENT COUNCIL OF ALBERTA

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2436970

FINAL REPORT

ON

RISKS ASSOCIATED WITH THE TRANSPORTATION TO TREATMENT OF HAZARDOUS WASTE SUBSTANCES

PHASE I

TO

ENVIRONMENT COUNCIL OF ALBERTA
EDMONTON, ALBERTA

BY

F. G. BERCHA AND ASSOCIATES LIMITED
CALGARY, ALBERTA

DECEMBER, 1980

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

The threat posed to industrialized regions by the accumulation of hazardous waste material has been dramatized recently by a number of incidents in which human populations have been exposed to hazardous wastes as the result of unsafe disposal practices. Within the province of Alberta, the dimensions of the industrial waste problem have been revealed in studies conducted by, or on behalf of, a number of government agencies. An inventory of hazardous wastes generation in Alberta [45] has estimated that 92,000 tonnes of wastes are produced in the province annually. As well as presenting difficult technical and logistic problems, the management of this volume of waste material has become a complex social issue. The public has become sensitized to the hazards of industrial wastes, and the proposed establishment of waste management programs, which will inevitably require transportation to treatment facilities of substantial amounts of waste, is perceived as a considerable threat by the residents of areas in which treatment or storage facilities may be built, or through which waste may be transported.

The present situation, with industrial waste accumulating in widely distributed locations of varying degrees of suitability and security, is becoming intolerable, and a program of waste collection and treatment is inevitable. However, a careful assessment must be made of the inherent risks of human exposure, environmental damage, and property damage before such a program is implemented. The general objective of the present study is the analysis of the risks of accidental release of industrial wastes during transportation from generating site to treatment facility. Because a uniform waste transportation system has not yet been defined for the province, the analysis was, of necessity, based on hypothesized characteristics of such a system. Furthermore, relevant historical data is scarce. Accordingly, direct probabilistic techniques that are suitable for the risk analysis of "history-less" systems were utilized in order to estimate the relative risks of various components of the waste transportation process, and to provide a general framework for the analysis of the transportation risks associated with waste disposal in the province of Alberta.

1.2 Background

Since the mid-1970's, a number of inventories and surveys [44, 45, 60] have demonstrated that large quantities of hazardous wastes are being generated in Alberta, and that current disposal practices are unsafe. Unregulated waste disposal has occurred in unsuitable and insecure locations, and hazardous materials have been discovered in the leachate from several landfill sites. As a solution to the waste management problem, Kinetic Contaminants Canada Limited proposed to build a waste disposal facility in Fort Saskatchewan; this proposal was met with great public resistance and led to the initiation of a series of public meetings conducted by the Environment Council of Alberta. As part of the investigation of the waste management issue, a number of studies were commissioned, including the hazardous waste inventory and review referred to above [45]. This inventory gives the most comprehensive picture currently available of the hazardous waste situation in Alberta.

Of the estimated 92,000 tonnes of waste materials generated annually by Alberta industries, the hazardous wastes inventory classifies 79,000 tonnes as "high priority" waste because of its hazard, volume, or bio-accumulation properties. Virtually all of this high priority waste consists of liquids, approximately 40% of which are flammable. About the same fraction consists of potentially corrosive liquids (although much of this waste is spent acids and alkalis which are relatively inactive). The properties of flammability and corrosiveness are, of course, potential contributing factors to transportation risk.

Current experience at landfill sites in Calgary and Edmonton is consistent with the inventory, and also suggests that the bulk of the wastes handled by waste management programs will be in liquid form. Most of the hazardous waste materials currently being deposited in these landfills are liquids transported in tank trucks. Almost all of these trucks are vacuum trucks (which are described in Chapter 2), although the inventory notes that a number of companies in the waste transport business also operate tractor-tank trailer units.

Thus, the most common waste disposal operation at present involves liquid waste transported in a tank truck. Landfill operators report that some semi-liquid sludges are brought to the site in bins or hoppers, and occasionally some materials are brought in drums, but that these cases account for a small proportion of the total waste deliveries.

1.3 Scope of Work

The present study is concerned with an analysis of the risks involved in the transportation of liquid industrial waste, and has been conducted in two phases. The scope of Phase I includes the analysis of the risk of waste spills during three operations:

(a) Loading of a tank truck at the waste generating site.

(b) Transport of the cargo to a temporary storage facility.

(c) Unloading of the tank truck cargo into storage.

Although the study deals mainly with several fairly specific hypothetical examples--the transport of wastes in two types of trucks to a particular type of storage facility--examples have been chosen to represent situations that are likely to be realized in the future, and the analysis methods are readily generalized to other situations.

Several alternative risk analysis methodologies could have been applied to the problem. Monte Carlo simulation methods, requiring the development of elaborate computer programs, have been applied to related transportation risk problems [13]. For the analysis to be meaningful, this approach generally requires the availability of an extensive data base for the definition of the probability distributions of important events, and for the definition of statistical relationships among the components of the system under study. In this study, a more basic risk analysis methodology was applied, one that was more appropriate to the extent of the project, and to the precision of the available data. The approach adopted is based on the fault tree analysis technique in which accidents are described in a manner that portrays the roles of important contributing risk factors and allows the quantitative estimation of risk levels corresponding to combinations of these factors. The fault tree analysis technique is discussed further in Chapter 3.

As would the other more complex simulation methods, this risk analysis technique addresses the essential problem: despite the absence of historical data that provides a complete, precise picture of the sources of risk, decisions must nonetheless be made as to the location of treatment or storage sites, the selection of routes and vehicle types, and the allocation of resources among preventive measures such as training and maintenance.

The fault tree analysis technique provides an analytic framework within which any relevant sources of data and information that are available may be exploited to the greatest extent possible in the decision-making process.

1.4 Project Outline

Five tasks were performed in Phase I of the study:

(a) Information gathering and familiarization.

(b) The development of risk scenarios.

(c) The quantification of risk probabilities and expected spill volumes.

(d) The generation of results.

(e) The development of conclusions and recommendations.

The results of these tasks are documented in this volume. Chapter 2 summarizes information on the physical system and operating procedures involved in waste transportation. Chapter 3 presents the analytical method, Chapter 4 describes the results, and Chapter 5 presents conclusions and recommendations based on the Phase I work.

In Phase II of the study, which is described in a separate report [5], the Phase I risk analysis results and methodology have been applied to the evaluationof the transportation risks associated with alternative locations of treatment facilities in the province.

CHAPTER 2

DESCRIPTION OF PHYSICAL SYSTEMS, OPERATING PROCEDURES, AND ACCIDENT TYPES

2.1 General Description

In the absence of an established system for transporting and storing hazardous waste in Alberta, the present analysis is necessarily based on a set of assumptions derived from a review of current practices in the province and elsewhere, and of an inventory of hazardous wastes in the province [1,7,17,42,45]. The analysis is directed towards what is expected to be the most common situation--the transportation of liquid wastes by truck. Truck transportation is most probable because of the geographic distribution of waste generating sites and their proximity to the road network, and liquid wastes account for most of the waste generated in Alberta [45].

The two truck types considered in the analysis - vacuum trucks and tank trailers - are the vehicles most commonly used for the transport of liquid hazardous waste. Other modes of transport include drums carried on flat-bed trucks or vans, and sludge bins carried on specialized trucks. These modes account for a small proportion of the waste material received at disposal sites.

The routes over which hazardous wastes will be transported in the province ultimately will depend on the location of storage and treatment facilities. The routes selected are an important determinant of risk levels because of the large variations among accident rates and severities for different kinds of routes. The risk analysis performed here has determined transportation risk levels for a variety of road types and for a set of assumed sample routes.

The risk analysis of loading and unloading operations is based on a set of assumptions regarding the physical layout of storage and pumping facilities at both ends of the transportation route, and the physical configuration of the tank truck. The vehicle and the cargo transfer equipment obviously determine the procedures that will be followed in loading and unloading operations. The systems and procedures assumed for the purpose of this analysis are based on various sources, including studies of storage facilities in other provinces [17], and other related studies [4, 7].

2.2 Transportation

2.2.1 Truck Types

The two truck types emphasized in this study, vacuum trucks and tank trailers, are both tank trucks designed for the transportation of liquid cargo but because of their different capabilities they are typically used in different circumstances. The vacuum truck is self-loading and may be used to draw waste from sumps or pits, or to draw up spilled liquid. Unlike the vacuum truck, the typical tank trailer is not self-loading, and is usually top-loaded using a hose and pumping equipment. Because of the requirement for loading equipment and because they generally carry large tanks, tank trailers tend to be used for transporting waste from major waste generation sites, and they also tend to be used in large waste recycling operations. These two types of tank truck account for virtually all of the liquid waste transportation in the province of Alberta.

2.2.2 Tank Trailer

Typical tank trailers are shown in Figures 2.1 - 2.2. The stainless steel, single compartment tank is equipped with manway cover and PV valves at the top, and a system of double outlet valves either at the side (Figure 2.3) or at the back (Figure 2.4), consisting of an external gate valve and an internal valve operated either hydraulically or by a spring loaded lever. The outlet line is blanked as shown in the figures. The capacity of the tank in the photograph is about 20,000 litres, which is fairly typical of the larger units used currently for waste transport [45].

2.2.3 Vacuum Trucks

The typical vacuum truck shown in Figures 2.5 to 2.8, is a more complicated piece of equipment than a tank trailer. A vacuum truck is usually a single unit truck equipped with a tank, and a pump that loads the liquid cargo by creating a vacuum in the tank. The tank is connected to the vacuum pump through a float valve mechanism that will terminate loading when the tank is full. Two lines, both equipped with valves, enter the rear of the tank at the top and bottom; the tank may be loaded through either line. One significant difference from tank trailers is that vacuum trucks may not have the double valve system on the loading lines. Other fittings on most vacuum trucks include a hatch at the rear of the tank for emptying sludge and other semi-liquid cargoes, and a manway at the top of the tank which provides access for cleaning and maintenance. The capacity of the pictured unit is 5,000 litres. A capacity of 10,000 litres is assumed in the present analysis, as being more typical of the middle size-range of the tank units[45].

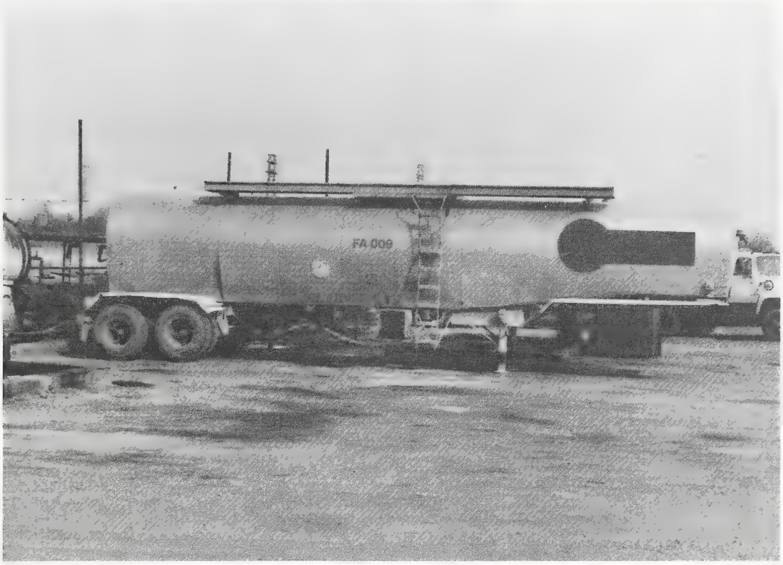


FIGURE 2.1   TANK TRAILER WITH OUTLET AT SIDE

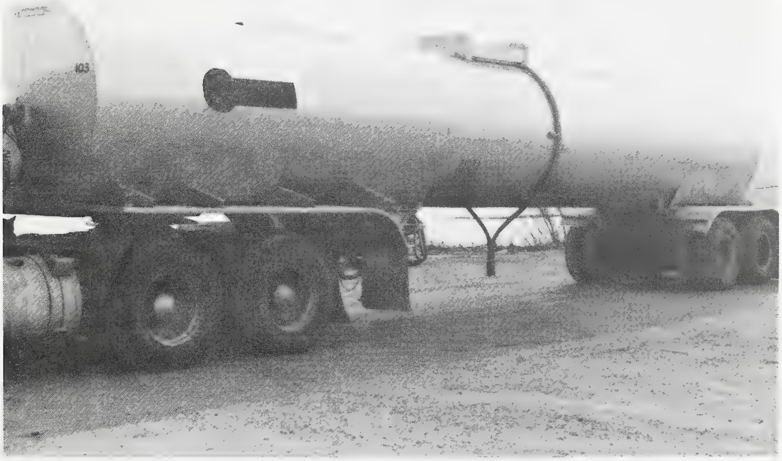


FIGURE 2.2   TANK TRAILER WITH BACK OUTLET

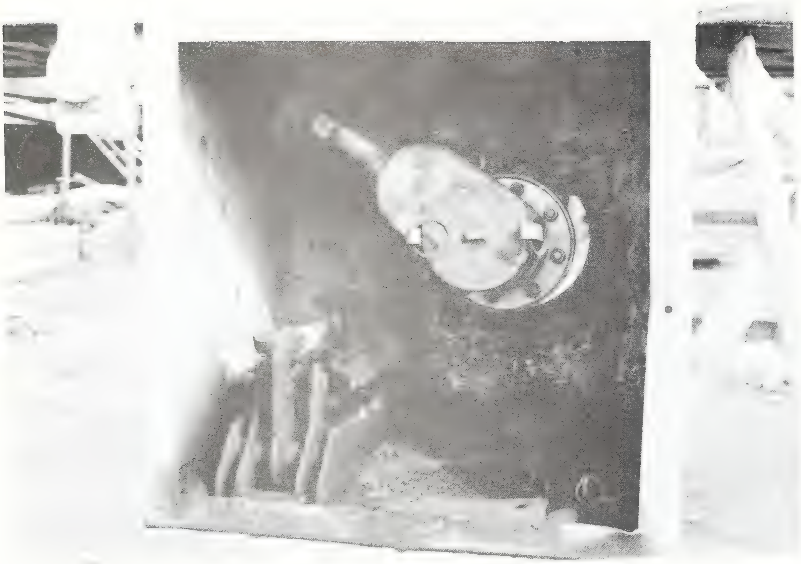


FIGURE 2.3 SIDE OUTLET VALVES ON TANK TRAILER

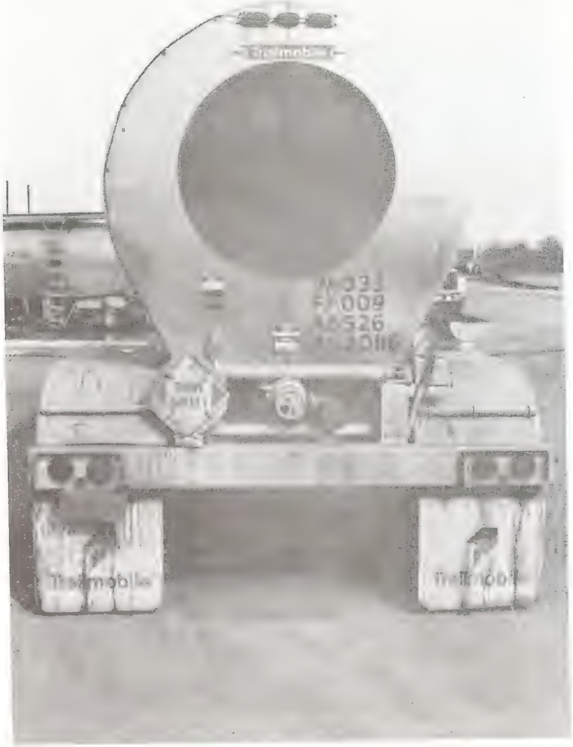


FIGURE 2.4

BACK OUTLET VALVES

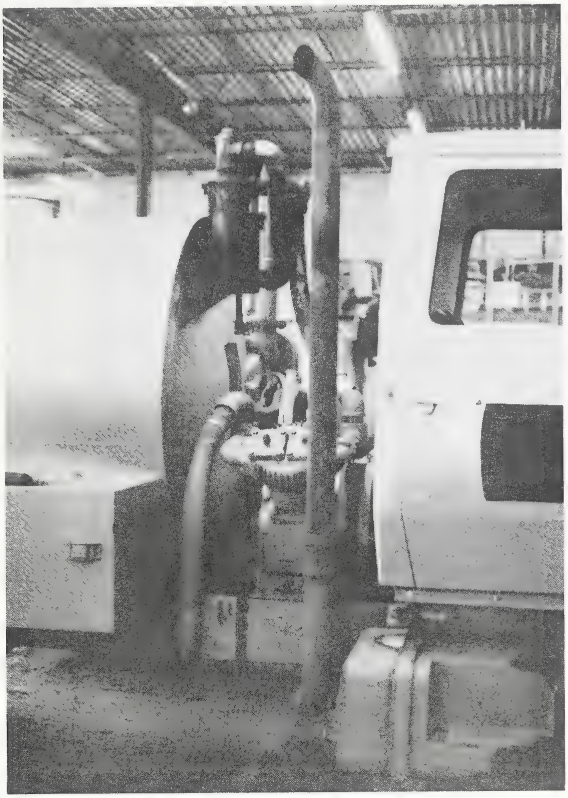


FIGURE 2.5

SIDE VIEW OF VACUUM TRUCK
SHOWING VACUUM PUMP WITH
FLOAT-VALVE MECHANISM AT TOP

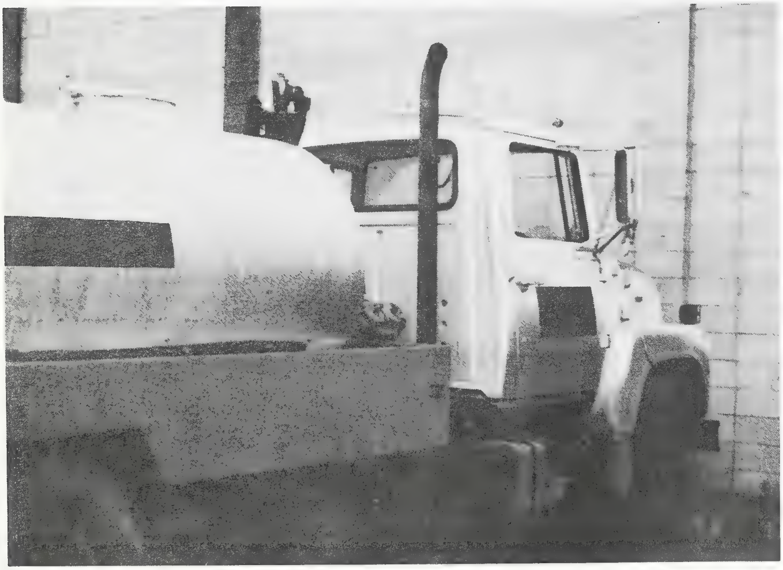


FIGURE 2.6 VACUUM TRUCK

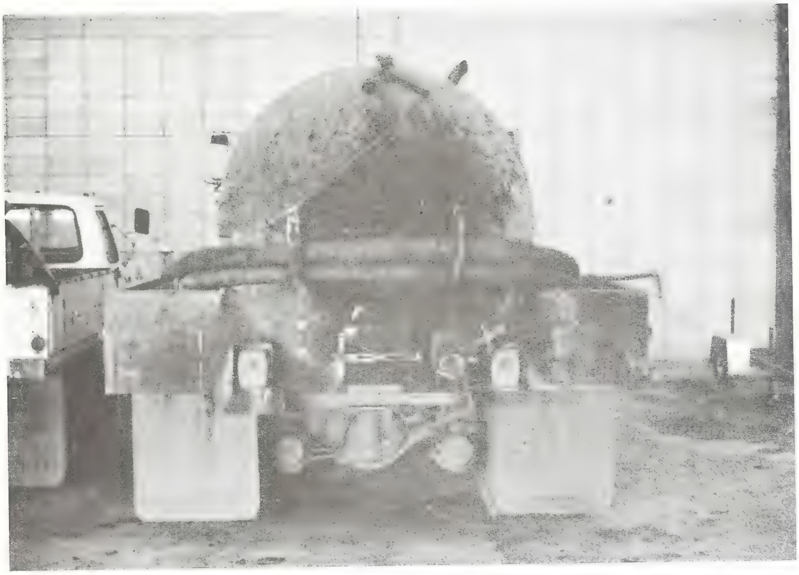


FIGURE 2.7 REAR VIEW OF VACUUM TRUCK SHOWING LOADING LINES
(Top Centre and Lower Right)

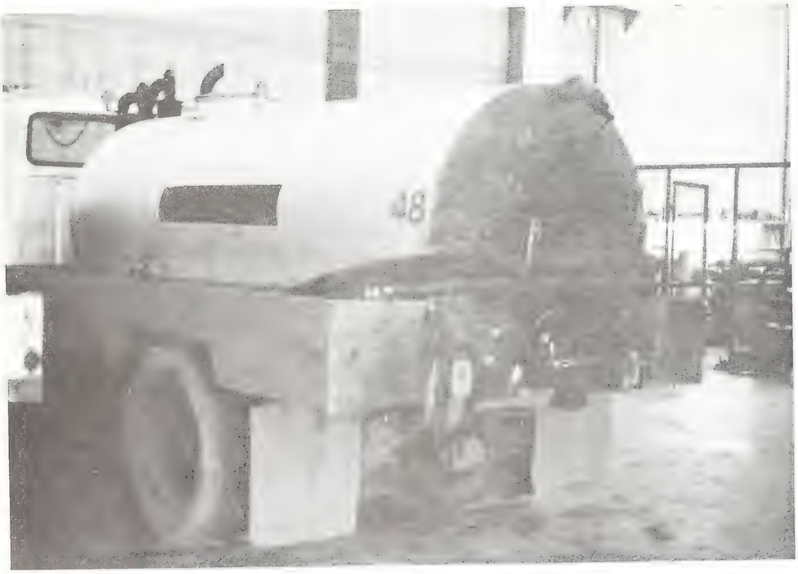


FIGURE 2.8 VACUUM TRUCK

2.2.4 Transportation Routes

The route over which hazardous wastes are transported is a very important factor in the risk analysis, since accident rates and accident severities vary substantially among the road types--primary highways, secondary highways, and urban streets--that will make up the segments of a transport route. A selection of representative route types has been considered in the present analysis. Spill rates have been computed for hypothetical routes consisting of various combinations of representative road segments of the three types. In addition, spill rates were computed for some actual routes that resemble probable hazardous waste transport routes.

2.3 Loading Operations

2.3.1 Tank Trailer Operating Procedures

Although some bottom loading systems are in use, tank trailers are usually loaded through the top manway using a hose connected to a pumping system. The steps in the loading procedure may be described briefly as follows:

(a) Check that the discharge valves are secure.

(b) Open the top hatch, insert the loading hose, open valves to the storage tank, and start the loading pump.

(c) Monitor the loading operation either visually, or using a flow meter if available.

(d) When loading is complete turn off the pump and storage tank valves, and remove the loading hose, draining any liquid left in the hose into a bucket or drain.

(e) Secure the loading hatch, and check the tank and truck valves for leaks.

2.3.2 Vacuum Truck Operating Procedures

Since the vacuum truck is self-loading the loading procedures are somewhat different than for the tank trailer. The operator connects the loading hose to either the top or bottom loading pipe and connects the other end of the loading hose to a standpipe if available, or submerges the end of the hose in the tank or pit containing waste. The vacuum pump is started and when the gauge on the truck indicates that the vacuum has been generated, the operator opens the truck valve on the loading pipe. The pump will be operated until the tank is full (detected either by a gauge or the sound of the pump) and the operator then closes the truck valve, turns off the pump, and disconnects the hose.

2.4 Unloading Operations

2.4.1 Storage Facilities

A waste storage facility would likely provide a number of different modes of truck unloading, including gravity unloading into a pit or tank and pumped unloading into an above-ground storage tank. Because of the ease of maintaining and monitoring above-ground storage tanks, they are the probable choice for liquid waste, and will be considered in the present analysis, although other storage equipment might be suitable for sludges and solid wastes.

There are several basic requirements for a waste storage facility: a dyked, protected, corrosion-resistant storage tank; pumps and lines for unloading trucks; vapour emission controls for the vapours displaced from the storage tanks during unloading and for the vapours produced during storage; drainage controls for spills and leaks; and foam equipment for fire control. The unloading facility assumed for the purposes of the present analysis is depicted in Figure 2.9. The facility consists of an above-ground storage tank equipped with a level indicator, pressure release valve, a vent line to return displaced vapours to the truck, and a vent line connecting the top of the tank to a set of scrubbers and filters. The truck feed hose is connected through a filter to a pump which in turn is connected to the tank filler line.

2.4.2 Operating Procedures

The unloading operating procedures for the tank trucks and the vacuum trucks are essentially the same. A truck driver arriving with a load of liquid waste would position the truck, connect the feed hose to the truck discharge line, connect the vent return line to the truck, open the truck valves and the valves labelled A, B, and C in Figure 2.9, and start the pump. A typical pumping time is less than one hour. When unloading is completed, the valves would be turned off, the pump shut down, and the truck hose disconnected and drained into a bucket or a sump drain.

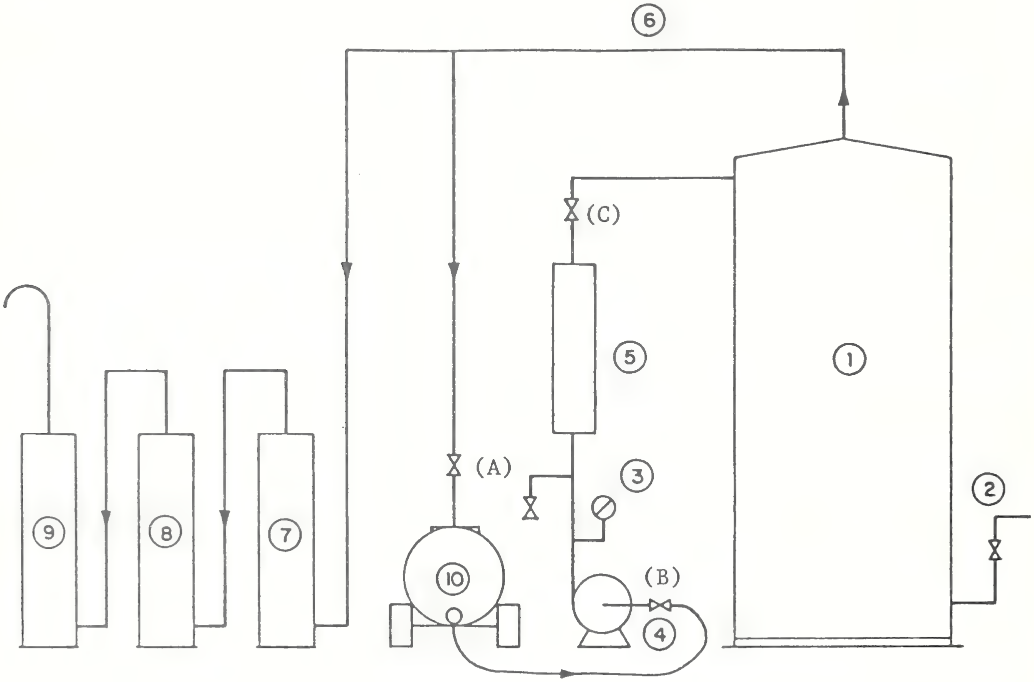
2.5 Accident Types

In the information gathering phase of the present study, basic accident types were identified for each of the loading, transport and unloading operations:

(a) Spills from the loading facility:

  (i) Due to equipment failure during loading: leak or rupture of gaskets, pump seals, valves, pipes, or storage tanks.

  (ii) Due to operator errors during loading: errors may occur in the operation of pump and valves, and in the monitoring of the unloading process.



① STORAGE TANK
② TANK DISCHARGE LINE
③ PRESSURE METER
④ TRUCK-TANK PUMP
⑤ FILTER (IF REQUIRED)
⑥ TO VAPOUR CONTROL SYSTEM
⑦ ⑧ ⑨ FILTER AND SCRUBBER
⑩ TRUCK

FIGURE 2.9 SCHEMATIC DIAGRAM OF LIQUID WASTE STORAGE SYSTEM

(b) Spills from the tanker truck:

  (i) Due to traffic accident.

  (ii) Due to other failures of the tank and valve system.

(c) Spills from the unloading facility:

  (i) Due to equipment failure during unloading.

  (ii) Due to operator error during unloading.

In addition, any of these types of release could occur as a result of a catastrophic event or as a result of sabotage.

In the case of flammable waste, any liquid spilled may be ignited by careless smoking, traffic accident conditions, exposure of spilled waste to electrical equipment, etc.

These accident types were analyzed in detail in the course of the present study to discover credible sequences of events that would produce them under realistic operating conditions. This analysis is presented in Chapter 3.

CHAPTER 3

ANALYSIS OF RELEASE RISKS

3.1 General Description of Analysis

The risk analysis of a system such as the transportation of hazardous wastes consists of two main phases: the gathering of information and the quantification of the information. The results of the information gathering phase have now been generally described in Chapter 2.

Quantification of the information consists of the generation of event probabilities, development of probabilistic logic networks called fault trees, and the generation of results. The general approach taken in the study is similar to that utilized by the writers for the analysis of drilling systems [5], marine safety systems [8], bulk storage plants [4], and PCB disposal operations [7]. These reports list many references on the background and development of the risk analytic techniques utilized for other applications such as nuclear reactor safety analysis as well as a thorough description of the modifications made to them by the writers in order to make them more workable for the type of systems considered in the present study.

In this chapter, a description will be given of the fault tree networks and their logic systems, of the associated probabilistic inputs, and of the investigation of specific risk factors. Results from the analysis will be presented in Chapter 4.

3.2 Fault Tree Networks

A fault tree network is a probabilistic logic network that represents an accident or system failure as the outcome of a sequence of occurrences leading from basic, initiating events, to an ultimate resultant event. In this particular case the resultant event being studied is the accidental release of hazardous wastes during truck loading, transportation, or unloading operations.

In addition to the identification of important contributing factors in accident events, fault tree analysis allows the estimation of failure probabilities of systems for which a long operating history is not available and whose performance cannot be forecasted using statistical prediction methods. It is generally possible to obtain statistical information on the performance of subsystems which have been components of other systems for which historical information is available. Essentially, the fault tree approach utilizes statistical data and other information relating to basic events which, although not observed within the context of the present system, have been observed under conditions that are sufficiently similar that their historical occurrence rates can serve as basic probabilistic inputs for the estimation of failure rates for the system under consideration.

Generally, the fault tree is evolved using a top-down recursive procedure. Starting with the supreme resultant event, the constituent main resultant events are identified.

The system is examined to determine the component and subsystem failures--human or mechanical--that can cause the top event. The logical relationships between these second level events and the top event are represented in the fault tree in two basic ways: events that must occur together to cause the top event are connected to the event through an AND gate, and a set of events, each of which is a sufficient cause, will be connected through an OR gate. The same process is then applied to the second level, and in this way, it is possible to recursively refine the event levels to a more and more basic set of events.

Figures 3.1 to 3.3 show the main components of the three fault tree networks developed for the hazardous waste transportation risk analysis. The trees depict the major accident scenarios for each of the loading, transport, and unloading phases of hazardous waste transportation. The accident scenarios in these trees were evolved from discussions with operators and government officials, observation of the physical systems and procedures involved in each phase, and investigation of the literature [4,7,17,25,27,42,45,46].

Analysis of transport operations indicated that three types of tank truck release incidents were possible, and thus the transportation fault tree has three main branches, corresponding to spills caused by traffic accidents, to other spills caused by material failure or operator error, and to cargo fires resulting from a spill incident.

Analysis of loading and unloading systems and operation resulted in the development of the scenarios represented in Figures 3.1 and 3.3 for the accidental release of liquid waste during the loading of the tank truck or during the transfer of the tank truck contents to storage tanks. The loading and unloading fault tree branches represent the spills that could occur because of operator errors or equipment failure during the initial hose connection and startup of the pump, during the pumping operation (including errors leading to tank overflow), or during the pump shutdown and hose disconnection steps. The accident sequences represented in the fault trees also include fire resulting from ignition of a spill, and releases due to catastrophe and sabotage.

In each of the three trees, the differences between vacuum trucks and tank trailers with respect to operating procedures and susceptibility to spills are represented using various "truck factors". For example, tank overflows during vacuum truck loading are controlled by a float valve mechanism, whereas overflow prevention for a tank trailer requires operator monitoring. The difference in the susceptibility to overflows is reflected in the failure probability calculations through the effect of a truck factor in the overflow branch of the loading tree.

For each major accident type, estimates have been calculated of the typical or modal volume of waste spilled in each incident, based on a combination of historical accident experience and analysis of relevant accident statistics in the literature [4,20,27,42,46,47,56]. These typical release volumes are termed "volume factors". There would be, of course, a great deal of variation in the volume spilled in a sample of occurrences of a given accident type; the time that elapses before an operator error or equipment failure is discovered may vary widely (as a result of varying degrees of operator alertness, for example). Thus, the volume factor is taken to be the modal, or most commonly occurring, spill volume of a distribution of volumes for a given accident type. The distributions used in this analysis are based on historical data giving spill volume distributions for handling and transport of liquid cargo in tank trucks. Once the probability of occurrence of an accident type has been calculated by evaluating and combining the corresponding subtree probabilities, the expected spill volume per trip or per operation for the accident type may be computed by computing an average of the spill sizes in the distribution, weighted by their probabilities of occurrence.

For the loading and unloading trees, the probability analysis is fairly straightforward--each basic event component of the accident subtrees may be assigned a single probability based on the nature of the operations involved and the probabilities of resultant events are calculated according to the well-known algebraic rules for combining probabilities. The traffic accident component of the transport tree, however, requires a more complex approach, since the probability of a traffic accident and the conditional probability that the accident is severe enough to cause a spill both depend upon the type of road being travelled, particularly on whether it is a primary highway, secondary road, or urban arterial. Thus, the probability of a spill due to a traffic accident on a particular route, P_T, depends on the length of the various road types making up the route and may be represented approximately by:

$$P_T = \sum_i \{L_i \times P_i \times S_i\}$$

where L_i is the total length of segments of roadway type i in the route, and P_i denotes the accident probability per unit length, and S_i the probability of a cargo spill in an accident, for roadway type i.

3.3 Basic Event Probabilities and Volume Estimates

The probabilistic inputs--the estimates of the basic event probabilities--are summarized in Table 3.1. This table shows the primary base event probability inputs utilized in the analysis, as well as the values of factors which modulate probability values at various points in the trees, or which give the modal volume factors for the accident types.

TABLE 3.1

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		RELEASE OF HAZARDOUS LIQUID WASTES DURING TRANSPORTATION	
I		Volume Released Due to Accident and Spill	
I_A		Volume Release Through Manifold Due to Accident	
	1	- Modal Volume Factor (F_{IA})	800ℓ/1000ℓ Transported
		[040] Spill Does Not Ignite	
A		Release Through Manifold Due To Accident (030)	
	2	- Severity Factor (conditional upon segment selected)	
A_1		Release Through Manifold	
	3	- Orientation Factor	0.84 (TT) 0.50 (VT)
	4	- Failure of Valve Assembly-Tank Mating Surface	1.6×10^{-3}/a
		Endcap Leaks Hazardous Wastes	
	5	- Endcap Faulty	1.1×10^{-2}/t
	6	- External Valve Open	7.0×10^{-3}/t (TT) 1.4×10^{-2}/t (VT)
	7	- Internal Valve Damaged	1.0×10^{-3}/a (TT) 1.0×10^{-3}/a (VT)
	8	- Endcap Damaged	1.0×10^{-6}/a
	9	- External & Internal Valves Open	5.8×10^{-5}/t (TT) 1.4×10^{-2}/t (VT)
		External Valve Assembly Leaks	

ℓ - litres
/a - per accident
/t - per trip
TT - Tractor Trailer
VT - Vacuum Truck

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	10	- External Valve Damaged	$7.2 \times 10^{-2}/a$
	11	- Internal Valve Open	$9.3 \times 10^{-3}/t$ (TT) $1.0 \times 10^{-3}/t$ (VT)
	12	- External Valve Faulty	$3.9 \times 10^{-5}/t$ (TT) $7.8 \times 10^{-5}/t$ (VT)
	13	- Internal Valve Damaged	$2.0 \times 10^{-3}/a$ (TT) $1.0 \times 10^{-3}/a$ (VT)
A_2		Accident on Segment (020)	
	14	- Length Factor (conditional upon segment selected)	
	15	- Traffic Accident (conditional upon segment selected)	
I_B		Volume Release Through Manway Cover Due to Accident	
	16	- Modal Volume Factor (F_{IB})	300ℓ /1000ℓ Transported
		[040] Spill Does Not Ignite	
A		Release Through Manway Cover Due to Accident (031)	
	17	- Severity Factor (conditional upon segment selected)	
A_1		Release Through Manway Cover	
	18	- Orientation Factor	0.2
	19	- Manway Cover Fails From Accident Forces	$2.4 \times 10^{-3}/a$
	20	- Manway Cover Faulty	$6.3 \times 10^{-3}/t$
A_2		(020) Accident on Segment	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
I_C		Volume Release Through Relief Valve Due to Accident	
	21	- Modal Volume Factor (F_{IC})	100ℓ/1000ℓ Transported
		[040] Spill Does Not Ignite	
A		Release Through Relief Valve Due to Accident (032)	
	22	- Severity Factor (conditional upon segment selected)	
A_1		Release Through Relief Valve	
	23	- Relief Valve Damaged	$1.0 \times 10^{-12}/a$
	24	- Orientation Factor	0.2
	25	- Relief Valve Faulty	$1.4 \times 10^{-2}/t$
	26	- Orientation Factor	0.2
	27	- Pressure Rise Opens Relief Valve	$5.7 \times 10^{-2}/a$
A_2		(020) Accident on Segment	
I_D		Volume Release Through Tank Walls Due to Accident	
	28	- Modal Volume Factor (F_{ID})	1000ℓ/1000ℓ Transported
		[040] Spill Does Not Ignite	
A		Release Through Tank Walls Due To Accident (033)	
	29	- Severity Factor (conditional upon segment selected)	
A_1		Release through Tank Walls	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	30	- Tank Crushed	$1.0 \times 10^{-12}/a$
	31	- Tank Punctured	$1.0 \times 10^{-12}/a$
	32	- Abrasion	$1.0 \times 10^{-2}/a$
	33	- Impact	$2.3 \times 10^{-2}/a$
	34	- Duration Factor	0.9
	35	- Fire	$1.6 \times 10^{-2}/a$
	36	- Relief Valves Fail	$7.1 \times 10^{-5}/a$
	37	- Undue Pressure Forces	$6.2 \times 10^{-4}/a$
II		Other Volume Release Due To Leak From Truck	
II_A		Volume Release Through Manway Cover	
	38	- Modal Volume Factor (F_{IIA})	Max. $5.0\ell/1000\ell$ Min. $2.4\ell/1000\ell$
		[041] Spill Does Not Ignite	
A		Release Through Manway Cover Per Trip (034)	
	39	- Length Factor (conditional upon segment selected)	
A_1		Leak From Manway Cover	
	40	- Spill Tops Retainer Cover Leaks	0.075(TT) 0.15 (VT)
	41	- Faulty Cover	2×10^{-4}(TT) 2×10^{-5}(VT)
	42	- Cover Not Properly Secured	1.5×10^{-4}(TT) 1.5×10^{-5}(VT)

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
II_B		Volume Release From Tank Body	
	43	- Modal Volume Factor (F_{IIB})	Max 15ℓ/1000ℓ Min 10ℓ/1000ℓ
		[041] Spill Does Not Ignite	
A		Release Through Tank Body Per Trip (035)	
	44	- Length Factor (conditional upon segment selected)	
A_1		Leak From Tank Body	
	45	- Tank Wall Defective	1.5×10^{-6}
	46	- Weld Failure	4.5×10^{-7}
II_C		Volume Release From Manifold	
	47	- Modal Volume Factor (F_{IIC})	Max 10ℓ/1000ℓ Min 5ℓ/1000ℓ
		[041] Spill Does Not Ignite	
A		Release From Manifold Per Trip (036)	
	48	- Length Factor (conditional upon segment selected)	
		Release From Manifold	
	49	- Loose/Defective Fittings and Valves	2.25×10^{-5} (TT) 3.0×10^{-5} (VT)
		Endcap Leaks	
	50	- Cap not Properly Installed	1.0×10^{-2}
	51	- Seal Leaks	1.0×10^{-3}

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		External Valve Not Secured	
	52	– Valve Faulty	4.0×10^{-3} (TT) 2.0×10^{-3} (VT)
	53	– Valve Not Properly Secured	3.0×10^{-3} (TT) 3.0×10^{-4} (VT)
		Internal Valve Not Secured	
	54	– Valve Faulty	7.0×10^{-3} (TT) 0.5×10^{-3} (VT)
	55	– Valve Not Properly Secured	3.0×10^{-4} (TT) 0.5×10^{-4} (VT)
II_D		Volume Release Due to Sabotage	
	56	– Modal Volume Factor (F_{IID})	Max 80ℓ/1000ℓ Min 40ℓ/1000ℓ
		[041] Spill Does Not Ignite	
A		Sabotage Per Trip (037)	
	57	– Length Factor (conditional upon segment selected)	
A_1		Sabotage	
	58	– Sabotage	9.0×10^{-6}
III		Volume Release Due to Cargo Fire	
III_A		Volume Release Due to Cargo Fire Resulting From Accident & Spill	
	59	– Modal Volume Factor (F_{IIIA_1})	800ℓ/1000ℓ Transported
		Ignition [040]	
	60	– Ignition	0.24
		(030) Manifold Release due to Accident	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	61	- Modal Volume Factor (F_{IIIA_2}) Ignition (042)	500ℓ/1000ℓ Transported
	62	- Ignition	0.24
		(031) Release Through Manway Due to Accident	
	63	- Modal Volume Factor (F_{IIIA_3})	100ℓ/1000ℓ Transported
		(042) Ignition	
		(032) Release Through Relief Valve Due to Accident	
	64	- Modal Volume Factor (F_{IIIA_4})	1000ℓ/1000ℓ Transported
		(042) Ignition	
		(033) Release Through Tank Walls Due to Accident	
III_B		Volume Release Due to Cargo Fire Resulting From Truck Leak	
	65	- Modal Volume Factor (F_{IIIB_1}) Ignition [041]	2.5ℓ/1000ℓ Transported
	66	- Ignition	0.01
		(034) Release Through Manway Per Trip	
	67	- Modal Volume Factor (F_{IIIB_2}) Ignition (043)	10ℓ/1000ℓ Transported
	68	- Ignition	0.01
		(035) Release Through Tank Body Per Trip	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	69	- Modal Volume Factor (F_{IIIB_3})	5ℓ/1000ℓ Transported
		(043) Ignition	
		(036) Release From Manifold Per Trip	
	70	- Modal Volume Factor (F_{IIIB_4})	20ℓ/1000ℓ Transported
		(043) Ignition	
		(037) Sabotage Per Trip	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		RELEASE OF HAZARDOUS LIQUID WASTES DURING THE TANK TRUCK LOADING OPERATION	
I		Volume Released Due To Tank Overflow	
		– Modal Volume Factor (F_I)	300ℓ
		[010] Spill Does Not Ignite	
I_A		Tank Overflow (011)	
	2	– Automation Factor	1.0
	3	– Automatic Shutoff Fails	1.0(TT) 0.1(VT)
A		Attempt to Overfill	
	4	– Tank Capacity < Tanker Load	0.9
A_1		Failure to Shutdown	
		Mechanical Failure	
	5	– Switch Failure	1.0×10^{-5}
	6	– Other	1.0×10^{-6}
	7	– Fail to Detect	3.0×10^{-2}
	8	– Procedural Error	5.0×10^{-3}
		Failure to Monitor	
	9	– Other	1.0×10^{-4}
		Gauging Errors	
		Mechanical Failure	
	10	– Gauge Fails	1.5×10^{-7}
	11	– Flow Meter Fails	1.5×10^{-5}

ℓ – litres
/a – per accident
/t – per trip
TT – Tractor Trailer
VT – Vacuum Truck

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		Operator Error	
	12	- Filling time inaccurate	1.5×10^{-3}
	13	- Flow meter not calibrated	1.5×10^{-3}
	14	- Ullage not Determined	1.5×10^{-3}
	15	- Rod misread	2.0×10^{-3}
II		Minor Volume Release During Pumping	
	16	- Modal Volume Factor (F_{II})	4.0ℓ
		[010] Spill Does not Ignite	
II_A		Minor Release During Pumping (012)	
	17	- Amplification Factor	6.0
	18	- Gaskets Leak	2.0×10^{-4}
	19	- Amplification Factor	0.5
	20	- Filling Line Leaks	6.0×10^{-5}
	21	- Amplification Factor	4.0
	22	- Packings Leak	5.0×10^{-6}
	23	- Amplification Factor	0.25
	24	- Hose Leaks	5.5×10^{-3}
III		Major Volume Release During Pumping	
	25	- Modal Volume Factor (F_{III})	250ℓ
		[010] Spill does not Ignite	
III_A		Major Release During Pumping (013)	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	26	– Truck Type Factor	1.0(TT) 0.5(VT)
A		Truck Discharge Valves Not Secure	
	27	– Truck Type Factor	1.0(TT) 0.0(VT)
	28	– Both Valves Open Due to Omission	1.0×10^{-4}
A_1		One Valve Open (other fails)	
	29	– External Omitted	3.0×10^{-3}
	30	– Internal Fails	2.0×10^{-7}
	31	– Internal Omitted	3.0×10^{-3}
	32	– External Fails	2.0×10^{-7}
B		Material Failure	
	33	– Amplification Factor	10.0
	34	– Packings or Gaskets Rupture	1.0×10^{-5}
	35	– Amplification Factor	4.0
	36	– Valve or Pump Casings Rupture	6.0×10^{-8}
	37	– Amplification Factor	0.50
	38	– Flowline Ruptures	4.0×10^{-9}
	39	– Amplification Factor	0.25
	40	– Hose Ruptures	5.5×10^{-5}
C		Accidental Separation of Flowline	
	41	– Other	1.0×10^{-8}
C_1		Undue Vehicle Movement	
	42	– Truck Struck by Another Vehicle	1.0×10^{-9}

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	43	- Grade Factor	0.1
		Vehicle Rolls Removing Line	
	44	- Hand Brakes not Set	3.0×10^{-3}
	45	- Wheel Chocks not in Place	3.0×10^{-3}
IV		Volume Release During Connection Procedure	
	46	- Flowline not Connected	1.0
	47	- Modal Volume Factor (F_{IVA})	10ℓ
		[010] Spill Does Not Ignite	
IV_A		Release Through Bottom Valve (014)	
	48	- Truck Type Factor	0.0(TT) 1.0(VT)
	49	- Truck Not Empty	0.1
	50	- Bottom Valve Opened	1.5×10^{-3}
	51	- Modal Volume Factor (F_{IVB})	100ℓ
		[010] Spill Does Not Ignite	
IV_B		Release From Storage Tank (015)	
A		Truck to Tank Valve Opened	
	52	- Mechanical Failure	2.0×10^{-7}
	53	- Operator Error	3.0×10^{-4}
	54	- Truck Type Factor	1.0(TT) 0.0(VT)
	55	- Pump Running	3.0×10^{-4}
	56	- Truck Type Factor	1.0(TT) 0.1(VT)

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	57	- Back Pressure From Tank	0.50
V		Volume Release At Shutdown	
	58	- Hose Disconnected/Removed	1.0
	59	- Modal Volume Factor (F_{VA})	100ℓ
		[010] Spill Does Not Ignite	
V_A		Release From Tanker/Bulk Storage Tank (016)	
	60	- Truck Type Factor	0.0(TT) 1.0(VT)
	61	- Bottom Valve Open	1.5×10^{-4}
A		Truck to Tank Valve Open	
	62	- Mechanical Failure	2.0×10^{-7}
	63	- Operator Error	3.0×10^{-4}
	64	- Truck Type Factor	1.0(TT) 0.0(VT)
	65	- Pump Running	3.0×10^{-4}
	66	- Truck Type Factor	1.0(TT) 0.1(VT)
	67	- Back Pressure From Bulk Storage Tank	0.75
	68	- Modal Volume Factor (F_{VB})	10ℓ
		[010] Spill Does Not Ignite	
V_B		Release From Hose (017)	
	69	- Failure to Control Hose Drainage	0.1ℓ
VI		Volume Release Due to Fire	
	70	- Modal Volume Factor (F_{VIA})	300ℓ

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		Ignition [010]	
	71	- Ignition	1.0×10^{-2}
		(011) Tank Overflow	
	72	- Modal Volume Factor (F_{VIB})	4ℓ
		Ignition (019)	
	73	- Ignition	1.0×10^{-2}
		(012) Minor Release During Pumping	
	74	- Modal Volume Factor (F_{VIC})	250ℓ
		(019) Ignition	
		(013) Major Release During Pumping	
	75	- Modal Volume Factor (F_{VID})	10ℓ
		(019) Ignition	
		(014) Release Through Bottom Valve	
	76	- Modal Volume Factor (F_{VIE})	100ℓ
		(019) Ignition	
		(015) Release From Storage Tank	
	77	- Modal Volume Factor (F_{VIF})	100ℓ
		(019) Ignition	
		(016) Release From Tanker/Bulk Storage Tank	
	78	- Modal Volume Factor (F_{VIC})	10ℓ
		(019) Ignition	
		(017) Release From Hose	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	79	- Modal Volume Factor (F_{VIH})	4000ℓ
		(019) Ignition	
		(018) Other Release	
	80	- Modal Volume Factor (F_{VIJ})	100ℓ
		(019) Ignition	
	81	- Hazardous Concentration of Vapour	
VII		Other Release Volume	
	82	- Modal Volume Factor (F_{VII})	4000ℓ
		[010] Spill Does Not Ignite	
VII_A		Other Release (018)	
	83	- Environmental Transgression	5.2×10^{-7}
	84	- Sabotage	6.1×10^{-7}

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		RELEASE OF HAZARDOUS LIQUID WASTES DURING THE TANK TRUCK UNLOADING OPERATION	
I		Volume Released Due to Tank Overflow	
	1	– Modal Volume Factor (F_1)	1800ℓ
		[010] Spill Does Not Ignite	
I_A		Tank Overflow (011)	
	2	– Automation Factor	1.0
	3	– Automatic Shutoff Fails	1.0
A		Attempt to Overfill	
	4	– Bulk Storage Tank Capacity < Tanker Load	0.1
A_1		Failure to Shutdown	
		Mechanical Failure	
	5	– Switch Failure	1.0×10^{-5}
	6	– Other	1.0×10^{-6}
	7	– Fail to Detect	1.0×10^{-2}
	8	– Procedural Error	1.0×10^{-3}
		Failure to Monitor	
	9	– Other	1.0×10^{-4}
		Gauging Errors	
	10	– Gauge Fails	1.5×10^{-7}

ℓ – litres
/a – per accident
/t – per trip
TT – Tractor Trailer
VI – Vacuum Truck

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	11	- Flow Meter Fails	1.5×10^{-5}
	12	- Float Stuck	1.0×10^{-2}
		Operator Error	
	13	- Filling Time Inaccurate	1.5×10^{-3}
	14	- Flow Meter Not Calibrated	1.5×10^{-3}
	15	- Ullage not Determined	1.5×10^{-3}
	16	- Rod Misread	1.5×10^{-3}
II		Minor Volume Release During Pumping	
	17	- Modal Volume Factor (F_{II})	4ℓ
		[010] Spill Does Not Ignite	
II_A		Minor Release During Pumping (012)	
	18	- Amplification Factor	6.0
	19	- Gaskets Leak	2.0×10^{-4}
	20	- Amplificiation Factor	0.25
	21	- Filling Line Leaks	6.0×10^{-5}
	22	- Amplification Factor	4.0
	23	- Packings Leak	5.0×10^{-6}
	24	- Amplification Factor	1.0
	25	- Hose Leaks	5.5×10^{-3}
III		Major Volume Release During Pumping	
	26	- Modal Volume Factor (F_{III})	250ℓ

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
		[010] Spill Does Not Ignite	
III_A		Major Release During Pumping (013)	
A		Material Failure	
	27	- Amplification Factor	10.0
	28	- Packings or Gaskets Rupture	1.0×10^{-5}
	29	- Amplification Factor	4.0
	30	- Valve or Pump Casings Rupture	6.0×10^{-8}
	31	- Amplification Factor	0.5
	32	- Flowline Ruptures	6.0×10^{-9}
	33	- Amplification Factor	0.5
	34	- Hose Ruptures	5.0×10^{-5}
	35	- Truck Type Factor	1.0
	36	- Faulty Connection	1.0×10^{-4}
B		Accidental Separation of Flowline	
	37	- Other	1.0×10^{-8}
B_1		Undue Vehicle Movement	
	38	- Tank Truck Struck by other Vehicle	1.0×10^{-9}
	39	- Grade Factor	0.1
		Vehicle Rolls Severing Line	
	40	- Hand Brakes Not Set	3.0×10^{-3}
	41	- Wheel Chocks Not In Place	3.0×10^{-3}

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
IV		Volume Release During Connection Procedure	
	42	- Flowline Not Connected	1.0
	43	- Modal Volume Factor (F_{IVA})	100ℓ
		[010] Spill Does Not Ignite	
IV_A		Truck Discharge Valves Open (014)	
	44	- Valves Opened by Operator	1.0×10^{-4}
	45	- Truck Type Factor	1.0(TT) 0.0(VT)
A		Other Valve Combination Failure	
	46	- Internal Valve Opened by Operator	3.0×10^{-3}
	47	- External Valve Fails	2.0×10^{-7}
	48	- External Valve Left Open	3.0×10^{-3}
	49	- External Valve Opened by Operator	3.0×10^{-3}
	50	- Internal Valve Left Open	3.0×10^{-3}
	51	- Internal Valve Fails	2.0×10^{-7}
	52	- Modal Volume Factor (F_{IVB})	10ℓ
		[010] Spill Does Not Ignite	
IV_B		Release From Storage Tank (015)	
	53	- Truck to Tank Valve Opened	3.0×10^{-3}
	54	- Liquid in Line	0.8
V		Volume Release at Shutdown	
	55	- Loading Hose Disconnected/ Removed	1.0

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	56	- Modal Volume Factor (F_{VA})	10ℓ
		[010] Spill Does Not Ignite	
V_A		Release From Tanker/Bulk Storage Tank (016)	
	57	- Truck Type Factor	1.0 (TT) 0.10(VT)
	58	- Back Pressure From Bulk Storage Tank	0.75
A		Truck to Tank Valve Open	
	59	- Mechanical Failure	2.0×10^{-7}
	60	- Operator Error	3.0×10^{-3}
	61	- Truck Not Empty	0.10
	62	- Truck Type Factor	0.0 (TT) 1.0 (VT)
	63	- Truck Type Factor	1.0 (TT) 0.0 (VT)
	64	- External Valve Fails at Closure	1.0×10^{-7}
	65	- External Valve Omitted	3.0×10^{-4}
B		Valve Combination Failure	
	66	- Both Valves Omitted	3.0×10^{-3}
	67	- External Valve Omitted	9.0×10^{-3}
	68	- Internal Valve Fails	2.0×10^{-7}
	69	- Internal Valve Omitted	9.0×10^{-3}
	70	- External Valve Fails	2.0×10^{-7}
	71	- Modal Volume Factor (F_{VB})	10ℓ
		[010] Spill Does Not Ignite	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
V_B		Release From Hose (017)	
	72	- Failure to Control Hose Drainage	0.10
VI		Volume Released Due to Fire	
	73	- Modal Volume Factor (F_{VIA})	1800ℓ
		Ignition [010]	
	74	- Ignition	0.01
		(011) Tank Overflow	
	75	- Modal Volume Factor (F_{VIB})	4ℓ
		Ignition (019)	
	76	- Ignition	0.01
		(012) Minor Release During Pumping	
	77	- Modal Volume Factor (F_{VIC})	250ℓ
		(019) Ignition	
		(013) Major Release During Pumping	
	78	- Modal Volume Factor (F_{VID})	100ℓ
		(019) Ignition	
		(014) Truck Disharge Valves Open	
	79	- Modal Volume Factor (F_{VIE})	10ℓ
		(019) Ignition	
		(015) Release From Storage Tank	

TABLE 3.1 (continued)

BASIC PROBABILITY INPUTS

Event No.	Input No.	Factor or Event Description	Value of Input
	80	- Modal Volume Factor (F_{VIF})	10ℓ
		(019) Ignition	
		(016) Release From Tanker	
		Bulk Storage Tank	
	81	- Modal Volume Factor (F_{VIG})	10ℓ
		(019) Ignition	
		(017) Release From Hose	
	82	- Modal Volume Factor (F_{VIH})	4000ℓ
		(019) Ignition	
		(018) Other Release	
	83	- Modal Volume Factor (F_{VI_J})	100ℓ
		(019) Ignition	
	84	- Hazardous Concentration of Vapour	
VII		Other Release Volume	
	85	- Modal Volume Factor (F_{VII})	
		[010] Spill Does Not Ignite	
VII_A		Other Release (018)	
	86	- Environmental Transgression	5.2×10^{-7}
	87	- Sabotage	6.1×10^{-7}

The probabilities are given as failures per operation for the loading and unloading trees, and failures per trip for the transportation tree. The outputs of the fault trees are ultimately converted to failure frequencies per million trips and expected volumes of waste released per million litres transported.

Ideally, the probability inputs would be based on reliable accident statistics for similar physical systems and operations, augmented as necessary with data gathered in field studies designed to estimate the probabilities of specific basic events. Such elaborate field studies are, of course, well beyond the scope of the present work. Furthermore, because of the uniqueness of the operations studied here, very little historical accident data is available that is applicable. Nevertheless, the fault tree representation of accidents as sequences of events leading from well-defined basic events reveals component activities of the operations that closely resemble activities that have been studied in other contexts. Thus, the input probabilities in Table 3.1 could be derived partly from relevant reliability literature [15,20,59] and previous studies [4,7,47,48]. In most cases, information from these sources was supplemented or modified by specific statistical data and subjective judgements provided in a number of interviews by personnel familiar with waste handling and transport operations. Some of the inputs for the transportation tree were derived from transportation risk studies [19,25,46], and discussions with officials of Alberta Transportation [29,49], the Ontario Ministry of Transportation and Communication, the federal Ministry of Transport, and the U.S. Department of Transportation [27].

3.4 Investigation of Risk Factors

Sensitivity analyses of several important risk factors were carried out, in order to investigate the changes in spill risk that would result from changes in the input probabilities for basic events that are related to the factors. Thus, for example, the effects of routing on spill risk were investigated by computing estimates of transportation spill frequency for a range of accident rates and severities typical of the variation in rates and severities that would be encountered in the province. Other factors that were investigated include the effects of training, fatigue, and experience on the operator error rate, equipment failures, the effects of maintenance on equipment errors, and the effects of cargo characteristics such as corrosiveness and flammability. Results of these analyses will be presented in Chapter 4.

3.5 Calculation Method

The actual calculations of estimated spill frequencies and volumes were performed using computer programs that include a fault tree evaluation package, and other programs developed specifically for this analysis. The contribution of this software to the risk analysis has been an important one. The programs do not, of course, create precise estimates from inprecise input data, but the automatic computation of spill estimates does render feasible the calculation tasks required for the evaluation of risk for many alternative sets of basic assumptions. Thus, it becomes possible to analyze the trends in relative risk that correspond to variations in basic risk factors, and to portray realistically the range of risk levels corresponding to the range of uncertainty in the input data.

CHAPTER 4

RESULTS

4.1 General Description

The results generated from the analysis and probabilistic inputs described in the previous chapter fall into two categories:

(a) Basic results, consisting of estimated frequencies of waste spills and spill volume expectations for the two truck types and the three major road types--primary highway, secondary highway, and urban arterial. These basic results consist of the calculated probabilities of occurrence of the top events of the fault trees of Chapter 3 (converted to rates of spill occurrence per million trips) and the expected volumes released (converted to volume spilled per 1,000,000 litres transported).

(b) Sensitivity analyses, which assess the sensitivity of the frequency and volume estimates to changes in the levels of the major risk factors. The factors investigated include operator error rates, equipment failure rates, and cargo characteristics.

These results are presented in Sections 4.2 and 4.3. Summaries of the important basic results and sensitivity analysis results appear in Sections 4.2.3 and 4.3.3. The reader may wish to read these summaries in place of the detailed analyses in Sections 4.2 and 4.3.

4.2 Basic Results

4.2.1 Transportation Basic Results

Figures 4.1 and Tables 4.1 and 4.2 present the basic risk analysis results for spills from tank trailers during the transport of non-flammable, non-corrosive cargo. The six curves in Figure 4.1 show the predicted frequencies and size profiles of spills for each of six road classes (defined below). Because the volume of cargo lost in transport spills tends to be proportional to cargo capacity [46], the volume of an accidental spill is measured in litres spilled per 1,000 litres of cargo carried. The frequencies are expressed as the number of spills per million trips. Thus, for example, the lowest curve in Figure 4.1 indicates that in one million tank trailer trips over one particular road type, about four spills will occur in which 30% to 100% of the cargo will be lost, about eight spills of 10% to 30%, and so on.

The six curves are grouped into three pairs. The top pair corresponds to two 100 km. primary highway routes, one route with a high accident rate, relative to a representative sample of Alberta primary highways [29], and one with a low accident rate. The middle pair corresponds to "high" and "low" 100 kilometer secondary highway routes, and the lowest pair corresponds to urban arterials. These six are not intended to represent realistic waste transportation routes but rather to illustrate several points that are important in the subsequent analysis. First of all, it is clear that accident rate affects the frequency of occurrence of large spills far more than that of small spills. This pattern reflects the fact that the small spills (depicted in Branch II of the transport tree) do not usually occur in traffic accidents, but rather are the results of equipment leaks or operator errors

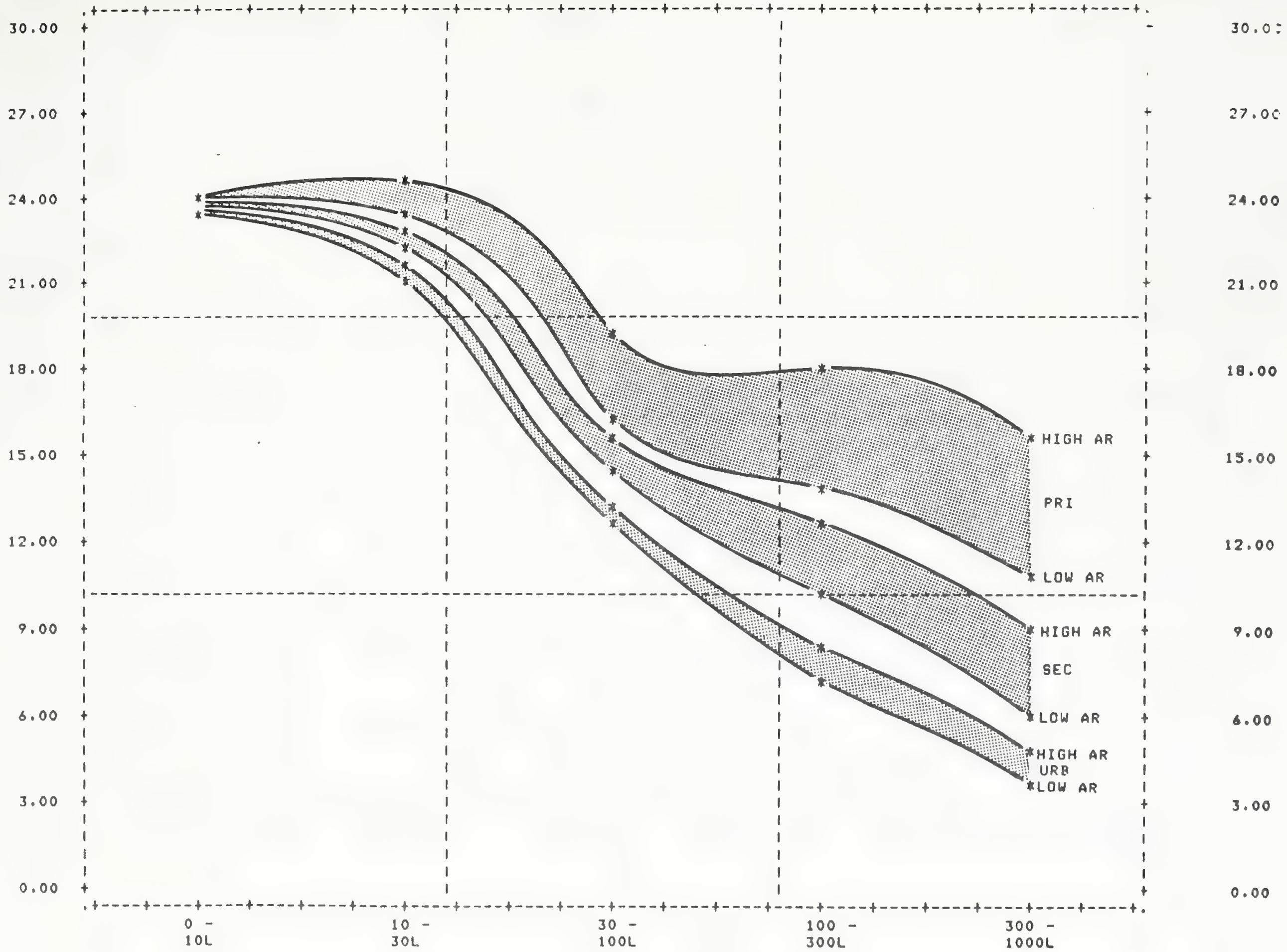


FIGURE 4.1 TRACTOR TRAILER, 100 KM. TRIP. NON-FLAMMABLE CARGO: SPILLS PER MILLION TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L)

TABLE 4.1

NUMBER OF CARGO SPILLS PER MILLION TRIPS:
TANK TRAILER, 100 KM. TRIP, NON-FLAMMABLE CARGO

	LOW PRIMARY	HIGH PRIMARY	LOW SECONDARY	HIGH SECONDARY	LOW URBAN	HIGH URBAN
UNDER 10L	23.63	23.84	23.46	23.58	23.34	23.39
10L - 30L	23.21	24.67	21.96	22.79	21.10	21.50
30L - 100L	16.47	19.01	14.29	15.75	12.80	13.50
100L - 300L	13.77	18.23	9.96	12.51	7.33	8.57
300L - 1000L	10.58	15.61	6.27	9.15	3.30	4.70
COLUMN TOTAL	88	101	76	84	68	72

TABLE 4.2

VOLUME OF CARGO SPILLED FOR EACH MILLION LITRES TRANSPORTED: TANK TRAILER, 100 KM. TRIP, NON-FLAMMABLE CARGO

	LOW PRIMARY	HIGH PRIMARY	LOW SECONDARY	HIGH SECONDARY	LOW URBAN	HIGH URBAN
UNDER 10L	0.12	0.12	0.12	0.12	0.12	0.12
10L - 30L	0.42	0.44	0.40	0.41	0.38	0.39
30L - 100L	0.92	1.06	0.80	0.88	0.72	0.76
100L - 300L	2.48	3.28	1.79	2.25	1.32	1.54
300L - 1000L	5.92	8.74	3.51	5.12	1.85	2.63
COLUMN TOTAL	9.85	13.65	6.60	8.80	4.40	5.45

in securing valves and fittings. The larger transportation spills occur in traffic accidents. Secondly, although it is well known that the average urban accident rate is much higher than the average rate for primary highways, Figure 4.1 shows that the frequency of accident-caused spill incidents is greater for primary highways. This reversal is a consequence of the relative severity of highway accidents. For a given road or road type, the proportion of tank truck accidents that will result in cargo spillage may be estimated using the relationship between spill rates and accident fatality rates for the road [46]. When this principle is applied to Alberta traffic statistics [49], the estimated severity of highway accidents more than compensates for low highway accident rates and produces the spill frequencies shown in Figure 4.1.

Tables 4.1 and 4.2 present results from the same analysis. The numerical results displayed graphically in Figure 4.1 are given in tabular form in Table 4.1, and Table 4.2 shows the expected total volume of waste spilled for each million litres transported by tank trailer. (For the assumed tank size of 20,000 litres, this corresponds to the total expected spill volume for 50 trips). As Table 4.2 shows, the expected loss in transport per million litres is quite small, ranging from 4.4 litres for the safest route to 13.6 litres for the route with the highest spill rate.

Figure 4.2 and Tables 4.3 and 4.4 repeat the analysis for vacuum trucks. Two important points should be noted in the vacuum truck results. First, Figure 4.2 shows that the estimated frequency of transportation spills from vacuum trucks is slightly greater than the tank-trailer frequencies discussed above, eventhough the typical vacuum truck studied here is a single unit truck or "straight truck" which should have a lower

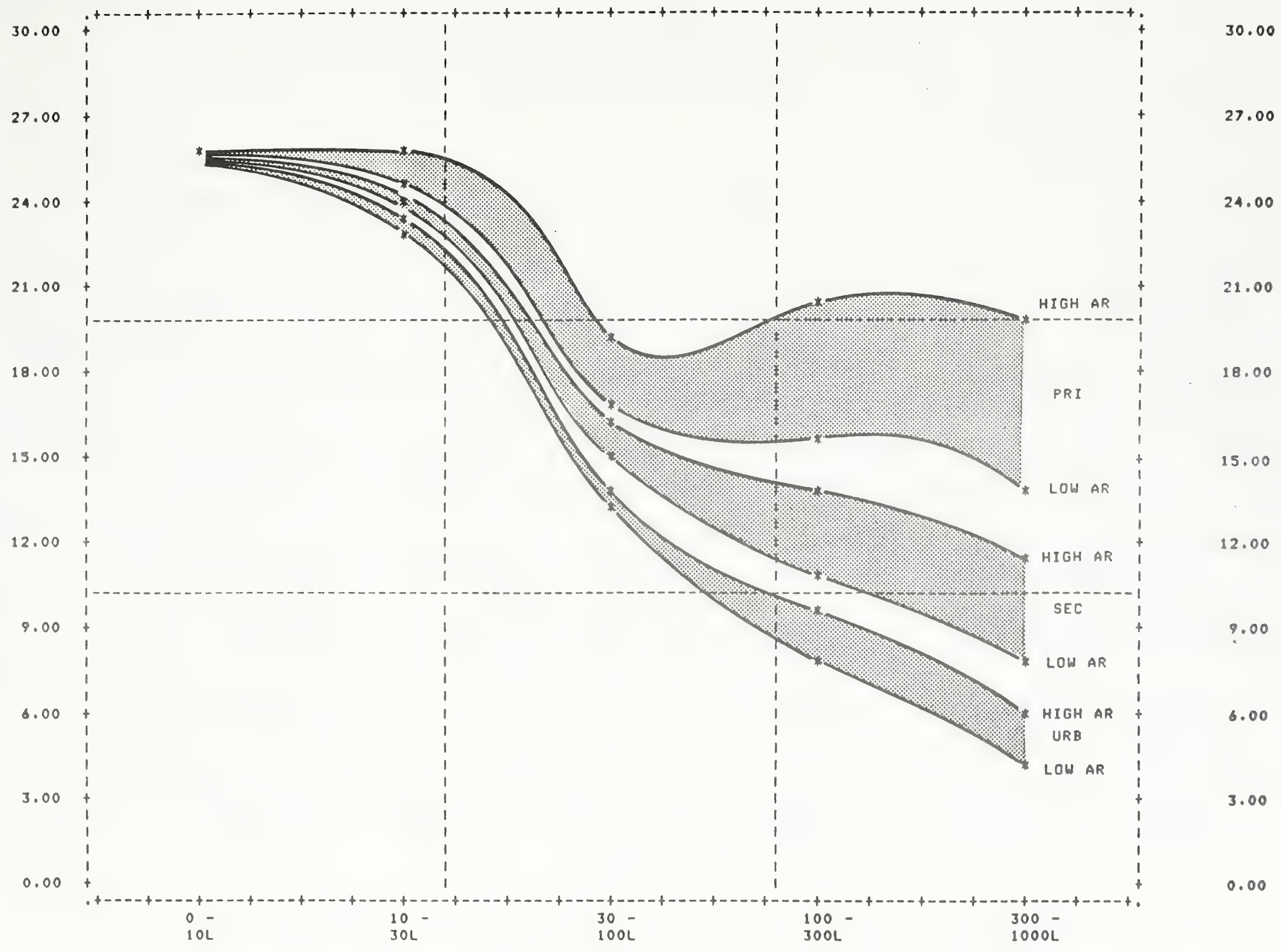


FIGURE 4.2 VACUUM TRUCK, 100 KM. TRIP, NON-FLAMMABLE CARGO: SPILLS PER MILLION TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L)

TABLE 4.3

NUMBER OF CARGO SPILLS PER MILLION TRIPS:
VACUUM TRUCK, 100KM. TRIP, NON-FLAMMABLE CARGO

	LOW PRIMARY	HIGH PRIMARY	LOW SECONDARY	HIGH SECONDARY	LOW URBAN	HIGH URBAN
UNDER 10L	25.70	25.84	25.58	25.66	25.50	25.54
10L - 30L	24.58	25.86	23.47	24.21	22.72	23.07
30L - 100L	16.77	19.09	14.78	16.11	13.41	14.06
100L - 300L	15.45	20.63	11.02	13.98	7.97	9.41
300L - 1000L	13.52	20.02	7.95	11.67	4.12	5.93
COLUMN TOTAL	96	111	83	92	74	78

TABLE 4.4

VOLUME OF CARGO SPILLED FOR EACH MILLION LITRES TRANSPORTED: VACUUM TRUCK, 100 KM. TRIP, NON-FLAMMABLE CARGO

- VACUUM TRUCK - 100KM TRIP - NON-FLAMMABLE CARGO

	LOW PRIMARY	HIGH PRIMARY	LOW SECONDARY	HIGH SECONDARY	LOW URBAN	HIGH URBAN
UNDER 10L	0.13	0.13	0.13	0.13	0.13	0.13
10L - 30L	0.44	0.47	0.42	0.44	0.41	0.42
30L - 100L	0.94	1.07	0.83	0.90	0.75	0.79
100L - 300L	2.78	3.71	1.98	2.52	1.44	1.69
300L - 1000L	7.57	11.21	4.45	6.54	2.31	3.32
COLUMN TOTAL	11.85	16.60	7.80	10.50	5.05	6.35

accident rate on a given road type than the larger tractor-trailer unit. For each route type, the vacuum truck accident rates used in this analysis were, in fact, lower than the rates used for tractor-trailers; the reduction factor was calculated by correcting published accident rates [11,19, 51] for the differences in exposure of the two truck types to different road types. The transportation fault tree analysis, however, predicts a higher probability of cargo spill during a vacuum truck accident than during a tractor-trailer accident, primarily because of the vacuum truck's greater number of external valves and fittings and lack of internal valve system. Therefore, although a vacuum truck will have fewer accidents, more of the accidents will result in cargo spills, thus producing a spill rate per million vehicle kilometers that is slightly greater than the tank-trailer rate.

The results in Table 4.4, showing the volume lost per million litres transported by vacuum truck, illustrates the second point. Although the average vacuum truck operates with about the same spill rate per vehicle kilometer as a tank trailer, and although more vacuum truck trips are required to transport one million litres, thus increasing accident exposure, the losses per million litres transported are roughly equal for the two truck types. The volume spilled in a vehicle accident is approximately proportional to vehicle capacity, and therefore, although a vacuum truck will have more spill accidents in transporting one million litres, the spill sizes will tend to be smaller than for a tank trailer.

The results discussed so far have been based on completely artificial routes, each consisting entirely of one road type, in order to demonstrate the effect of road type on spill rate. Figures 4.3 and 4.4, and Tables 4.5 to 4.8 present frequency and volume estimates for vacuum truck and tank

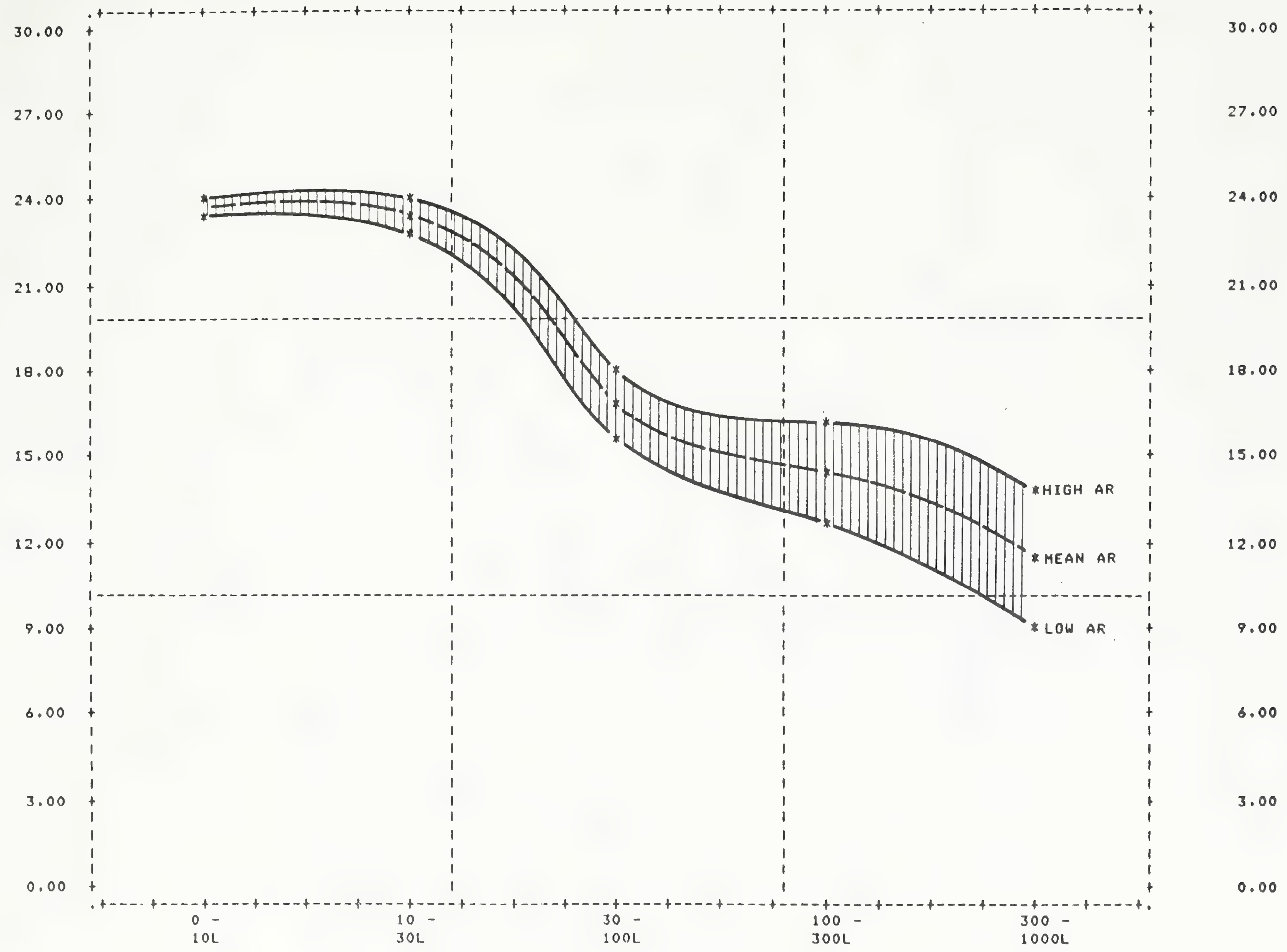


FIGURE 4.3 TRACTOR TRAILER, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER MILLION TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L)

TABLE 4.5

NUMBER OF CARGO SPILLS PER MILLION TRIPS: TANK TRAILER, 100 KM. MIXED ROUTE, NON-FLAMMABLE CARGO

	LOW AR	MEAN AR	HIGH AR
UNDER 10L	23.58	23.67	23.76
10L - 30L	22.83	23.46	24.10
30L - 100L	15.81	16.91	18.02
100L - 300L	12.61	14.55	16.49
300L - 1000L	9.27	11.46	13.65
COLUMN TOTAL	84	90	96

TABLE 4.6

VOLUME OF CARGO SPILLED PER MILLION LITRES TRANSPORTED: TANK TRAILER, 100 KM. MIXED ROUTE, NON-FLAMMABLE CARGO

	LOW AR	MEAN AR	HIGH AR
UNDER 10L	0.07	0.07	0.07
10L - 30L	0.41	0.42	0.43
30L - 100L	0.89	0.95	1.01
100L - 300L	2.27	2.62	2.97
300L - 1000L	5.19	6.42	7.64
COLUMN TOTAL	8.85	10.50	12.15

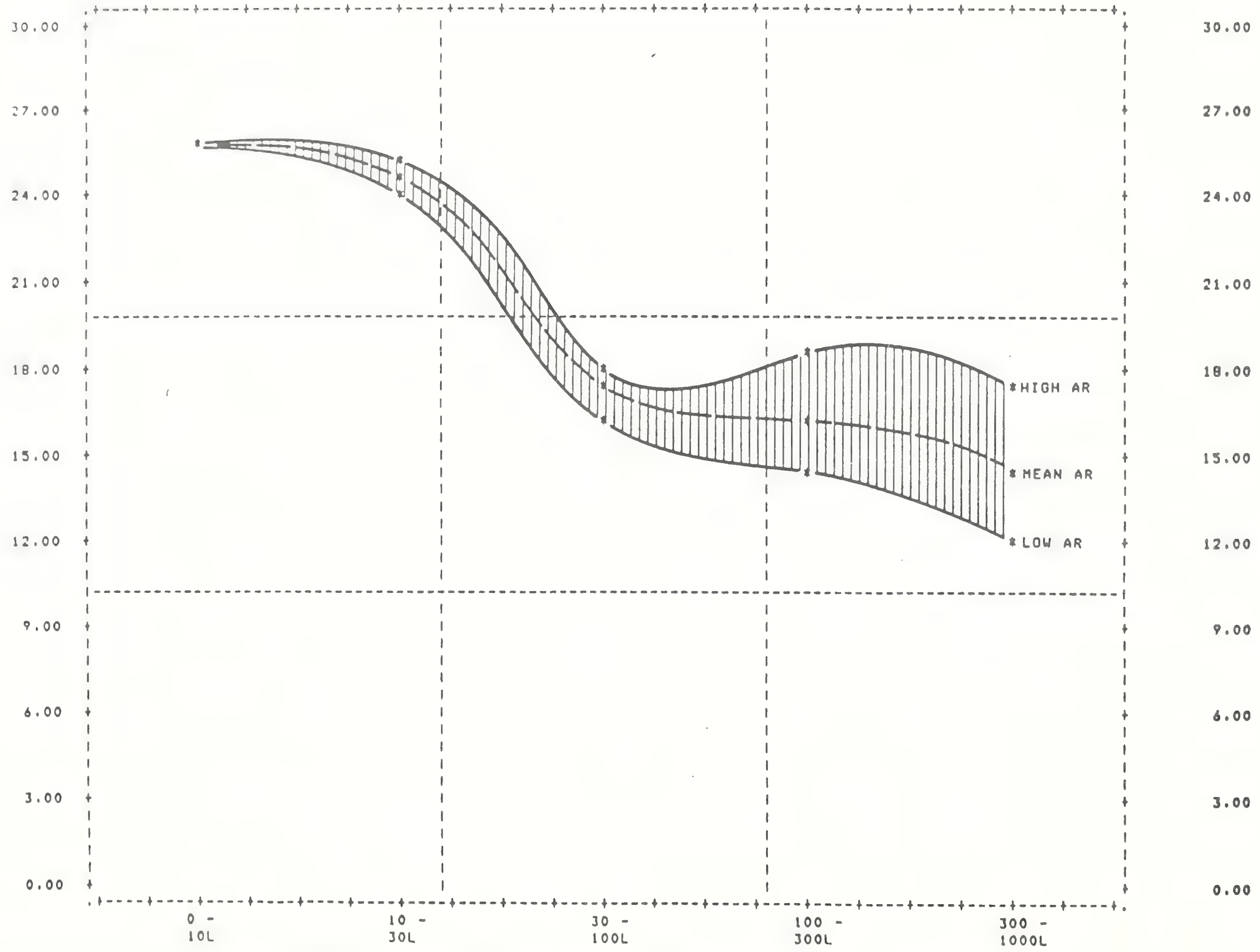


FIGURE 4.4 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L)

TABLE 4.7

NUMBER OF CARGO SPILLS PER MILLION TRIPS: VACUUM TRUCK, 100 KM. MIXED ROUTE, NON-FLAMMABLE CARGO

	LOW AR	MEAN AR	HIGH AR
UNDER 10L	25.66	25.72	25.78
10L - 30L	24.24	24.80	25.36
30L - 100L	16.17	17.18	18.19
100L - 300L	14.11	16.36	18.61
300L - 1000L	11.83	14.66	17.49
COLUMN TOTAL	92	99	105

TABLE 4.8

VOLUME OF CARGO SPILLED PER MILLION LITRES TRANSPORTED: VACUUM TRUCK, 100 KM. MIXED ROUTE, NON-FLAMMABLE CARGO

	LOW AR	MEAN AR	HIGH AR
UNDER 10L	0.08	0.08	0.08
10L - 30L	0.44	0.45	0.46
30L - 100L	0.91	0.96	1.02
100L - 300L	2.54	2.94	3.35
300L - 1000L	6.62	8.21	9.79
COLUMN TOTAL	10.60	12.65	14.70

trailer spills on a hypothetical 100 km. route which is more representative of possible waste transport routes. The route consists of a mix of primary highway (80 kilometers), secondary road (5 kilometers), and urban road (15 kilometers). Frequency and volume estimates were computed for both the "high" and "low" segment accident rates; results computed for average segment accident rates are also presented. To summarize the results of the analysis of truck differences, Figure 4.5 combines in one graph the spill frequencies for tank trucks and vacuum trucks on this average route; the frequency and volume results are also presented in Tables 4.9 and 4.10.

4.2.2 Loading and Unloading - Basic Results

Figure 4.6 and Table 4.11 show the predicted volume and frequency estimates for spills during loading and unloading operations. The volume classes in the loading and unloading analysis are actual spill volumes, unlike those in the transportation analysis, where accident spill volumes tend to be proportional to tank capacity, and so were reported as litres spilled per 1,000 litres. The estimated spill frequencies are plotted on a logarithmic scale in Figure 4.6 in order to accommodate the wide range of values.

It is clear from Figure 4.6 that accidents during transfer operations range from infrequent large spills to very frequent minor releases. Over 90% of the expected transfer spills released less than 30 litres; most of these resulted from careless hose disconnection procedures and minor equipment leaks. Table 4.12 shows that, despite their small size, these spills could account for about 80% of the total expected volume of waste spilled during transfers.

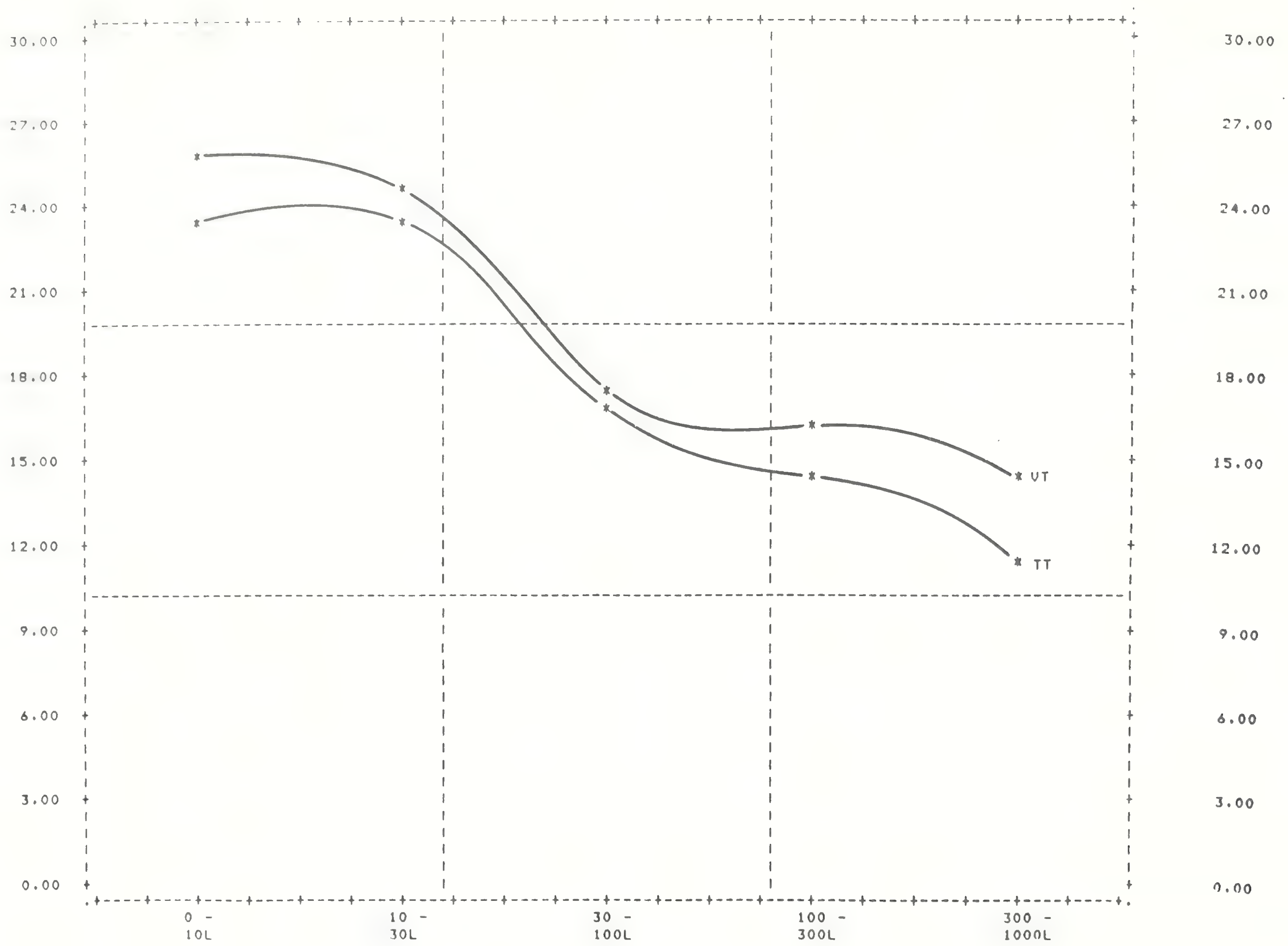


FIGURE 4.5 BOTH TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS SPILL VOLUME (L PER 1000 L)

TABLE 4.9

NUMBER OF CARGO SPILLS PER MILLION TRIPS FOR EACH TRUCK TYPE ON 100 KM. AVERAGE ROUTE

	TRACTOR TRAILER	VACUUM TRUCK
UNDER 10L	23.67	25.72
10L - 30L	23.46	24.80
30L - 100L	16.91	17.18
100L - 300L	14.55	16.36
300L - 1000L	11.46	14.66
COLUMN TOTAL	90	99

TABLE 4.10

VOLUME OF CARGO SPILLED PER MILLION LITRES TRANSPORTED FOR EACH TRUCK TYPE ON 100 KM. AVERAGE ROUTE

	TANK TRAILER	VACUUM TRUCK
UNDER 10L	0.07	0.08
10L - 30L	0.42	0.45
30L - 100L	0.95	0.96
100L - 300L	2.62	2.94
300L - 1000L	6.42	8.21
COLUMN TOTAL	10.50	12.65

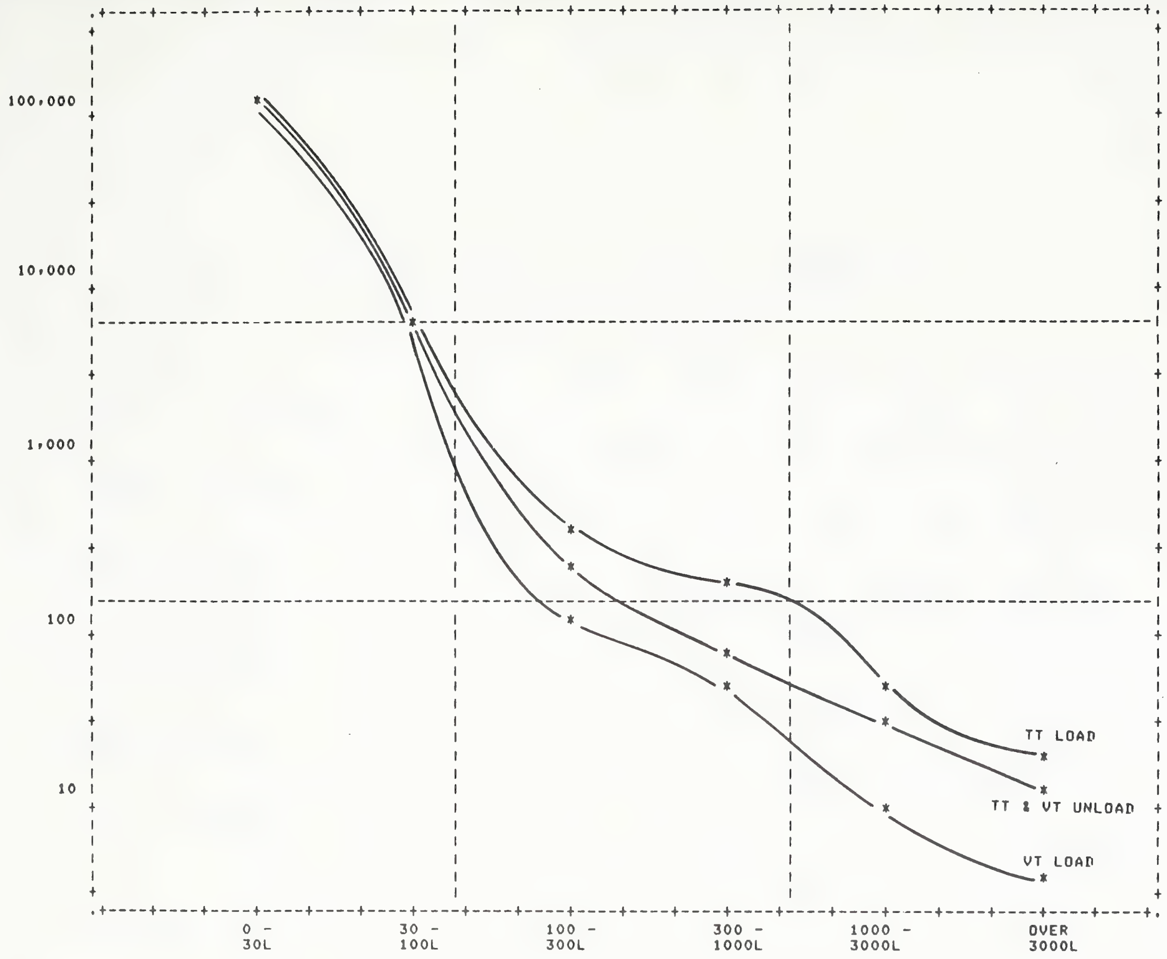


FIGURE 4.6 LOADING AND UNLOADING, NON-FLAMMABLE CARGO: SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL

TABLE 4.11

NUMBER OF LOADING AND UNLOADING SPILLS PER MILLION TRIPS FOR EACH TRUCK TYPE

	TT LOADING	TT UNLOADING	VT LOADING	VT UNLOADING
UNDER 30L	103200.00	107700.00	103300.00	107400.00
30L - 100L	5360.00	5491.00	5195.00	5465.00
100L - 300L	307.20	191.80	89.58	179.20
300L - 1,000L	159.40	64.41	44.0	61.89
1,000L - 3,000L	41.42	23.5	8.36	23.37
OVER 3,000L	16.45	10.41	3.09	10.41
COLUMN TOTAL	109084	113481	108640	113140

TABLE 4.12

VOLUME OF CARGO SPILLED IN LOADING AND UNLOADING PER MILLION LITRES TRANSPORTED FOR EACH TRUCK TYPE

	TT LOADING	TT UNLOADING	VT LOADING	VT UNLOADING
UNDER 32L	92.88	96.93	185.94	193.32
32L - 100L	15.01	15.37	29.09	30.60
100L - 300L	2.76	1.73	1.61	3.23
300L - 1,000L	4.46	1.80	2.47	3.47
1,000L - 3,000L	3.73	2.12	1.50	4.21
OVER 3,000L	4.61	2.91	1.73	5.83
COLUMN TOTAL	123	121	222	241

Differences between truck types, and between loading and unloading operations, appear in the expected frequencies of larger spills. In order to highlight these differences, the hose disconnections and minor equipment leaks have been removed from the spill distributions and the results displayed in Figure 4.7, and Tables 4.13 and 4.14. Reflecting the fact that the unloading procedures are virtually identical for the two types of trucks, the unloading frequency estimates are indistinguishable in Figure 4.7. There are, however, substantial differences in loading spill frequencies; tank trailer loading spills are over three times as common as vacuum truck loading spills, and release over twice as much waste. These differences are attributable mainly to the more frequent occurrence of overflow spills in the loading of tank trailers. (The typical vacuum truck has an automatic cut-off valve).

4.2.3 Review of Basic Results

Table 4.15 summarizes the basic results for an average 100 km. transport route that includes both highway and urban segments. The table shows that, over the long run, cargo losses due to spills would amount to 0.05% of the liquid waste carried by a vacuum truck, and 0.025% of the waste carried by a tank trailer. The difference between the two tank trucks is primarily the result of the difference in capacities of the two typical trucks analyzed here--the vacuum truck tank is half the size of the tank trailer, and is thus exposed to spill risks twice as often during the transport of one million litres.

Virtually all of the spilled liquid waste is released during transfer operations and most of that waste is spilled in small amounts during hose disconnection.

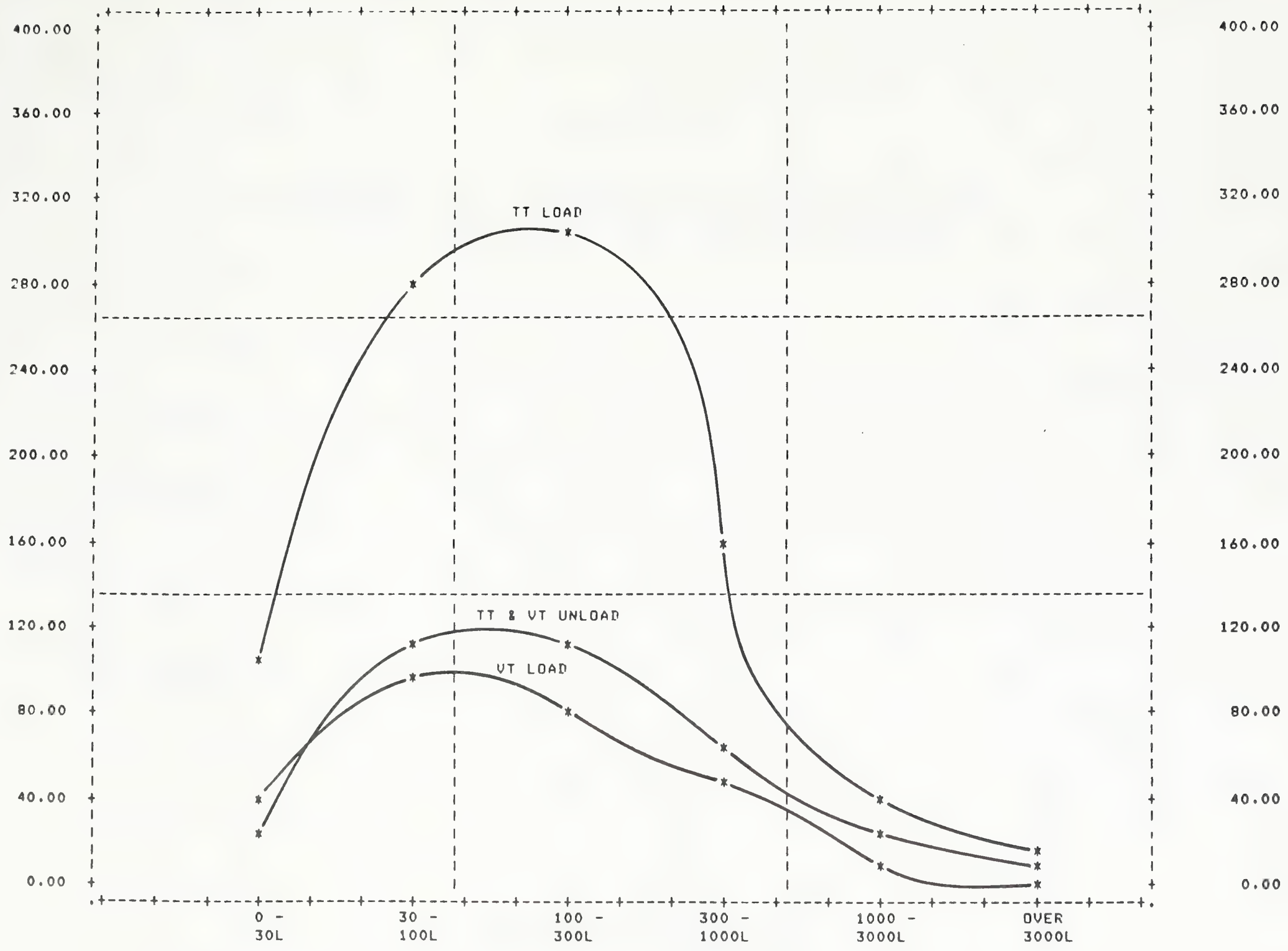


FIGURE 4.7 LOADING AND UNLOADING NON-FLAMMABLE CARGO: SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (SMALL SPILLS REMOVED)

TABLE 4.13

NUMBER OF LOADING AND UNLOADING SPILLS PER MILLION TRIPS FOR EACH TRUCK TYPE; SMALL SPILLS REMOVED

	TT LOADING	TT UNLOADING	VT LOADING	VT UNLOADING
UNDER 30L	107.30	23.60	40.73	20.00
30L - 100L	277.90	111.10	98.16	103.90
100L - 300L	307.20	115.30	82.08	110.80
300L - 1,000L	159.40	64.41	44.0	61.89
1,000L - 3,000L	41.42	23.5	8.36	23.37
OVER 3,000L	16.45	10.41	3.09	10.41
COLUMN TOTAL	910	348	276	330

TABLE 4.14

VOLUME OF CARGO SPILLED IN LOADING AND UNLOADING PER MILLION LITRES TRANSPORTED FOR EACH TRUCK TYPE; SMALL SPILLS REMOVED

	TT LOADING	TT UNLOADING	VT LOADING	VT UNLOADING
UNDER 30L	0.10	0.02	0.07	0.04
30L - 100L	0.78	0.31	0.55	0.58
100L - 300L	2.76	1.04	1.48	1.99
300L - 1,000L	4.46	1.80	2.47	3.47
1,000L - 3,000L	3.73	2.12	1.50	4.21
OVER 3,000L	4.61	2.91	1.73	5.83
COLUMN TOTAL	16	8	8	16

TABLE 4.15

VOLUME SPILLED PER MILLION LITRES TRANSPORTED FOR BOTH TRUCK TYPES IN LOADING, TRANSPORT AND UNLOADING

	VACUUM TRUCK	TANK TRAILER
LOADING	222	124
TRANSPORT	12	10
UNLOADING	241	121
TOTAL	475	255

A somewhat different picture emerges when large spills are considered alone. Table 4.16 shows a breakdown for each truck type of the volume released in spills larger than 3,000 litres. In this table, the truck differences average out over the loading--transport--unloading sequence. Unloading procedures and risks are virtually identical for the two trucks and thus the effect of capacity difference is still evident in the volume spilled during unloading. This difference, however, is counter-balanced by the greater frequency of spill accidents in tank trailer loading operations, primarily due to the frequency of overflow accidents.

Table 4.16 also shows that transportation accidents account for about 50%,by volume, of the large spills. This figure perhaps understates the importance of transportation accidents, since they are much more likely to have serious consequences than are transfer spills which may be controlled effectively by drainage systems. Transportation accidents occur in unpredictable locations under uncontrolled conditions and may expose many people to the spilled material, although it is reassuring to note that transportation spill rates on urban streets are shown in Section 4.2.1 to be substantially lower than rural highway rates. Thus, the population along the urban portion of a waste transport route would be exposed to fewer spills per vehicle kilometer than would the environment of rural highways.

4.2.4 Comparison of Basic Results with Statistical Information

Basic results of this analysis were compared with relevant statistical records whenever possible, in order to provide at least an approximate verification of these results. Because no available statistical information is detailed enough to verify the individual predictions computed in the study, only very general comparisons will be made.

TABLE 4.16

VOLUME SPILLED PER MILLION LITRES TRANSPORTED FOR BOTH TRUCK TYPES IN LOADING, TRANSPORT AND UNLOADING (SPILLS LARGER THAN 3000 LITRES)

	VACUUM TRUCK	TANK TRAILER
LOADING	1.7	4.6
TRANSPORT	8.2	8.0
UNLOADING	5.8	2.9
TOTAL	15.7	15.5

The transport spill rates computed here were based on a number of assumptions regarding a relationship between road type and the probability of a cargo spill in an accident, and were estimated from a number of data sources [19,17,19,46,49]. When these estimates were used in the transport risk analysis an average spill rate of about 30 accident-caused spills per one hundred million vehicle kilometers was predicted. This proportion compares quite well with the range of spill rates, 10 - 40 per hundred million vehicle kilometers, that was reported in a small study of Alberta tank truck spills [42].

An attempt was also made to verify the relationship between the rates of non-accident spills, including transport spills occurring because of equipment failures, loading spills, and unloading spills, and the rates of traffic accident spills. Although several relevant sources of data were discovered, the reported ratios vary widely, depending on the function of the institution that gathered the data, and on the extent to which the statistics could be affected by reporting bias. Thus, of the transport spills reported by Alberta Transportation in a survey of accidents involving dangeroug goods [2], 100% occurred in traffic accidents. Alberta Environment records of hazardous spill incidents [42] indicate that voluntarily reported spills of petroleum products from tank trucks occur in traffic accidents, non-accident equipment failures, and during loading and unloading, in the approximate ratio of 14:4:5. The U.S. Department of Transportation, to which a Hazardous Materials Incident Report must be sent for any hazardous material spill during transport or temporary storage, reports a ratio of approximately 11:11:37 [27], showing the effect of compulsory reporting on the apparent rates of non-accident spills.

It seems clear that spills in traffic accidents, being highly visible events, are far more likely to be reported than other incidents, particularly when the reporting is voluntary. Even the reports received by D.O.T. is thought to greatly underestimate non-accident spill rates, perhaps by as much as 90% [27]. Therefore, the average estimates produced by this analysis--approximately 30 traffic accident spills for every 60 fitting or equipment failure spills and 900 significant loading and unloading spills--are judged to be acceptable.

4.3 Investigation of Risk Factors

4.3.1 Transportation Sensitivity Analyses

The sensitivity of the frequency of transportation waste spills to various risk factors has been evaluated by varying the probability of basic events associated with the factors and re-evaluating the spill probabilities for a vacuum truck travelling on the average route. Because of the volume of output that is generated by this and subsequent sensitivity analyses, the analysis was performed for only one truck type and one route. The pattern of results for other truck types and routes would be similar.

Figure 4.8 shows the changes in spill volume frequencies that occur when the input probabilities for operator error vary from 50% to 150% of their original value. (The operator errors referred to here include only errors relating to the operation of the tank and its ancillary equipment--driver errors are considered below). Figure 4.9 shows the results of a similar sensitivity analysis performed for equipment failures involving the tank and ancillary valve fittings. It is apparent that in contrast to the accident rate, both classes of error contribute primarily to the smaller spills, although they have some effect on larger accident-caused spills as

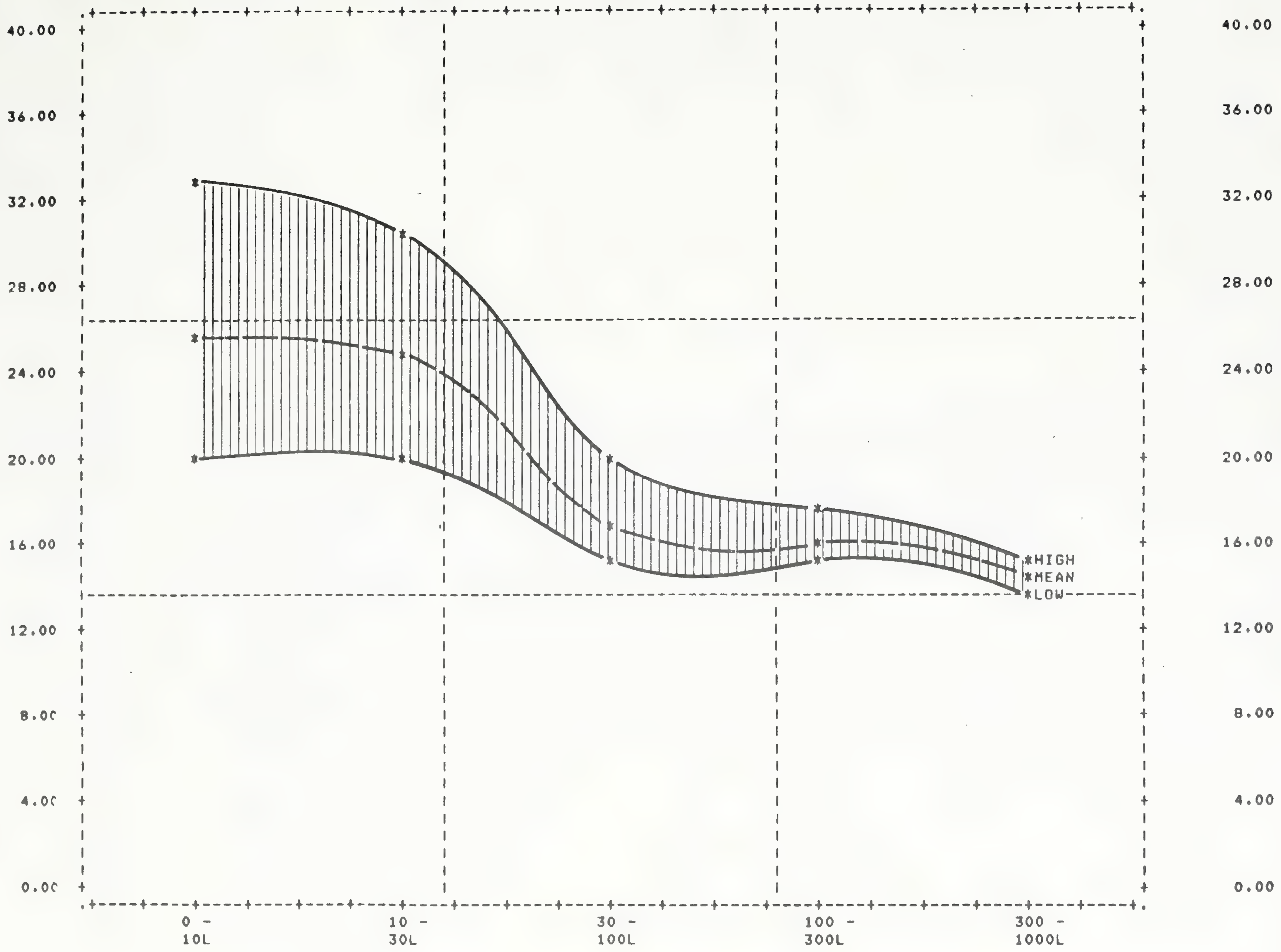


FIGURE 4.8 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L); SENSITIVITY TO OPERATOR ERRORS

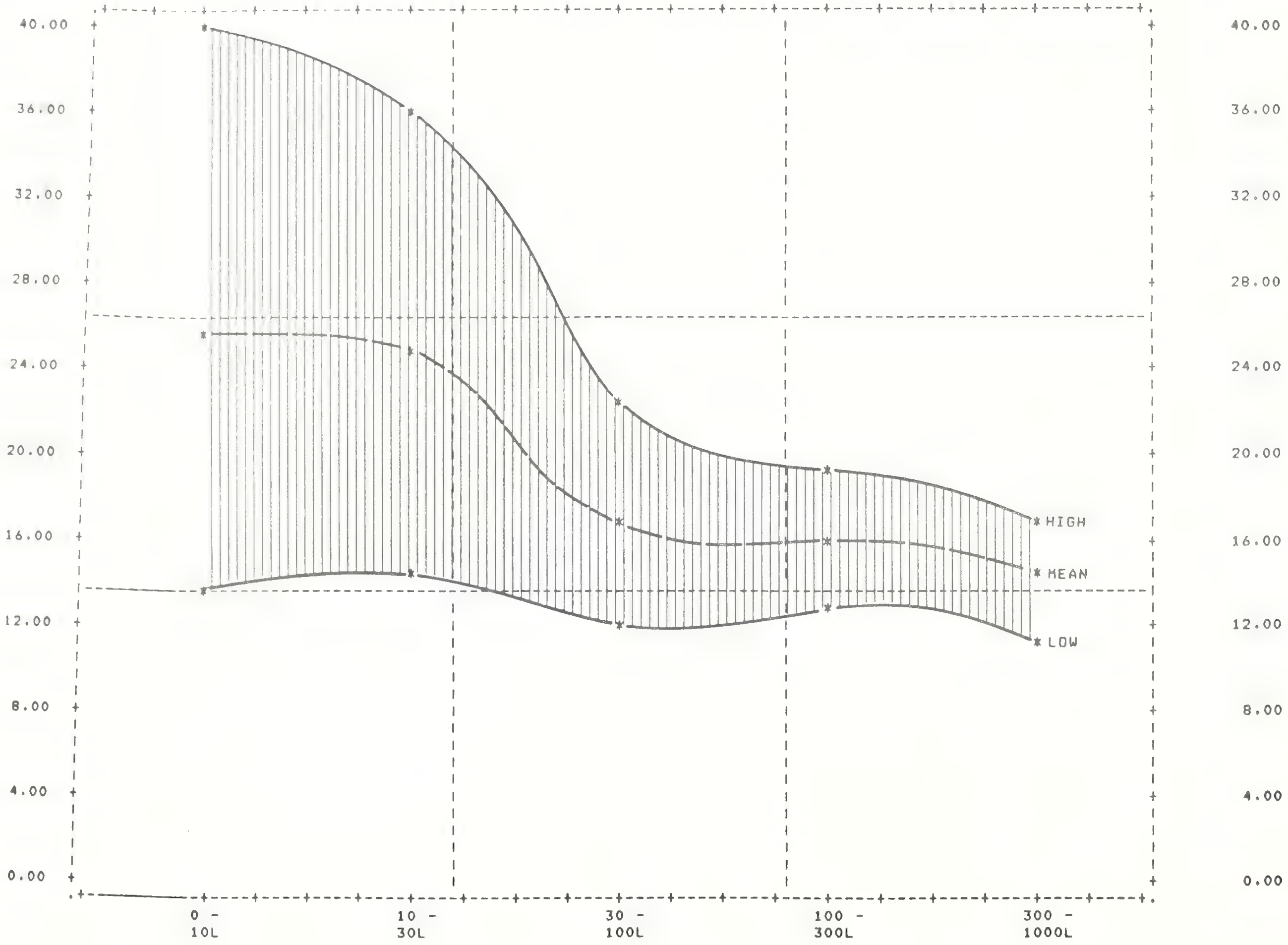


FIGURE 4.9 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L); SENSITIVITY TO EQUIPMENT FAILURE

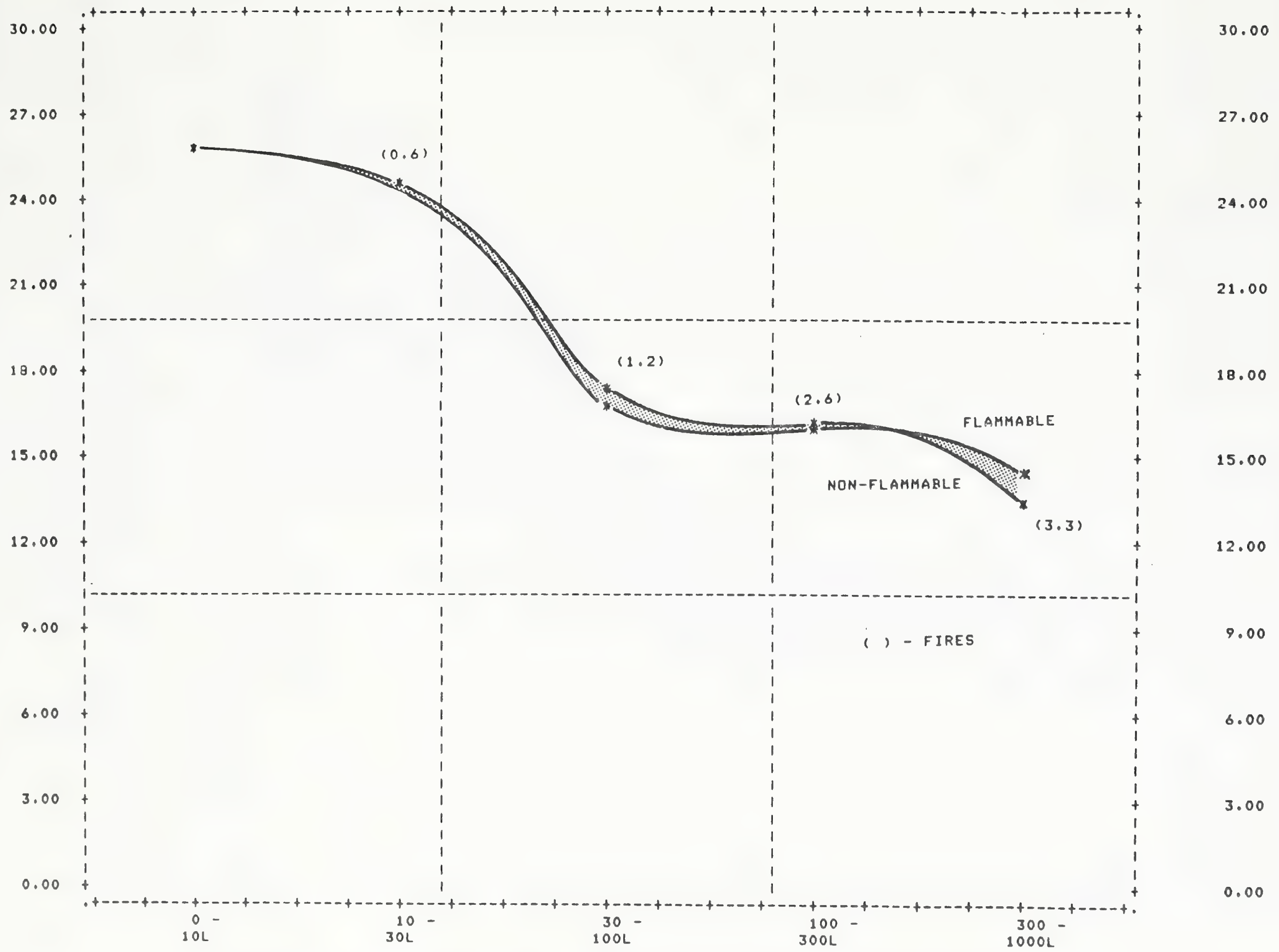


FIGURE 4.10 VACUUM TRUCK, 100 KM. MIXED ROUTE: FLAMMABLE AND NON-FLAMMABLE CARGOES

well, reflecting the effect of some equipment and operation faults on the probability of a cargo release in a traffic accident. The variation in input probabilities for operator errors and equipment failures induces changes in the expected spill volume of ±8%, and ±20%, respectively, relative to the "mean value" computed from the original inputs.

The sensitivity of risk to cargo characteristics was also investigated, the results are displayed in Figures 4.10 for flammability and 4.11 for corrosiveness. The spill size profile for flammable cargo shown in Figure 4.10 includes spills which ignite; the average volume spilled is slightly larger, reflecting the fact that ignition of a spill results in a larger release. Ignition of accident-caused spills of flammable cargo which occurs in about 24% of such spills [31], will usually result in loss of most of the cargo [46]. About 1% of the larger non-accident releases will ignite [27], resulting in an order-of-magnitude increase in the volume released, because of the difficulty in controlling the release once fire has started. For flammable cargo the total predicted release volume per million litres is slightly greater than for the non-flammable base case; the number of fires occurring in each spill volume category are noted in Figure 4.10.

In the calculations for Figure 4.11, it was assumed that corrosivenes of the cargo doubles the probability of failure of valves, fittings, welds, and the tank wall. This assumption was based on U.S. Department of Transport Hazardous Materials Incident Reports [27] for highway transport of corrosive materials in tank trucks with tanks designed for the transport of corrosives (D.O.T. Specifications MC 310, 311, 312 [9]). Most of these records relate to spills of product, which would usually be more reactive than "corrosive waste", and the effects of corrosion may be overestimated.

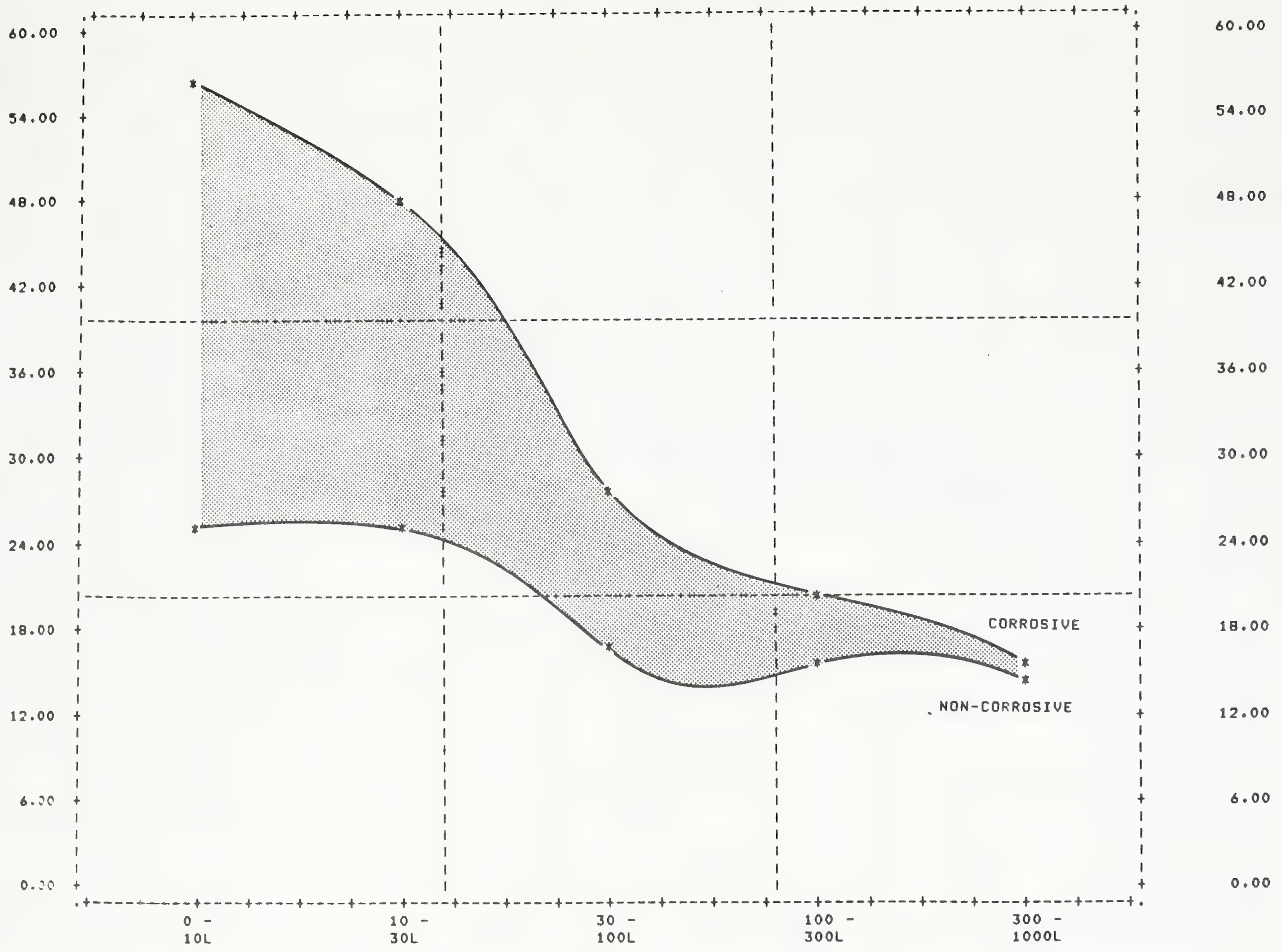


FIGURE 4.11 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L); SENSITIVITY TO CORROSIVE CARGO

As Figure 4.11 shows, the assumed effect of corrosiveness on failure rate translate into an increase in spill frequency, mainly for smaller equipment related spills, and a change in the total expected volume release for million litres of about 25%.

The analyses described in this section have dealt with risk factors that affect the probabilities of groups of basic events. Another set of important factors--vehicle maintenance, driver fatigue, and driver training--effect the probability that a given driver or a given vehicle will have an accident of a particular type. The importance of these factors in determining overall transportation risk was evaluated by estimating the potential affect on highway and urban accident probabilities, and then re-calculating transportation spill frequency and volume estimates with the altered accident rates.

Truck accidents in which the primary accident cause is a vehicle defect are most often single-vehicle highway accidents [37,51,55]. From the statistical data published in the cited references, it is estimated that 11% of the highway truck accident rate and 4% of the urban truck accident rate is attributable to vehicle defects. These figures are consistent with other published reports dealing with passenger cars [39,50], although they do reflect the tendency of trucks to have a higher percentage of defect-related accidents. If maintenance programs eliminated all such accidents, the reduction in accident rates would produce the changes in spill volume distributions that are depicted in Figure 4.12. The total expected transportation spill volume would drop by about 8%. Although these results are based on a rather optimistic assumption regarding maintenance effectiveness, they do give an approximate picture of the potential safety benefits of maintenance programs.

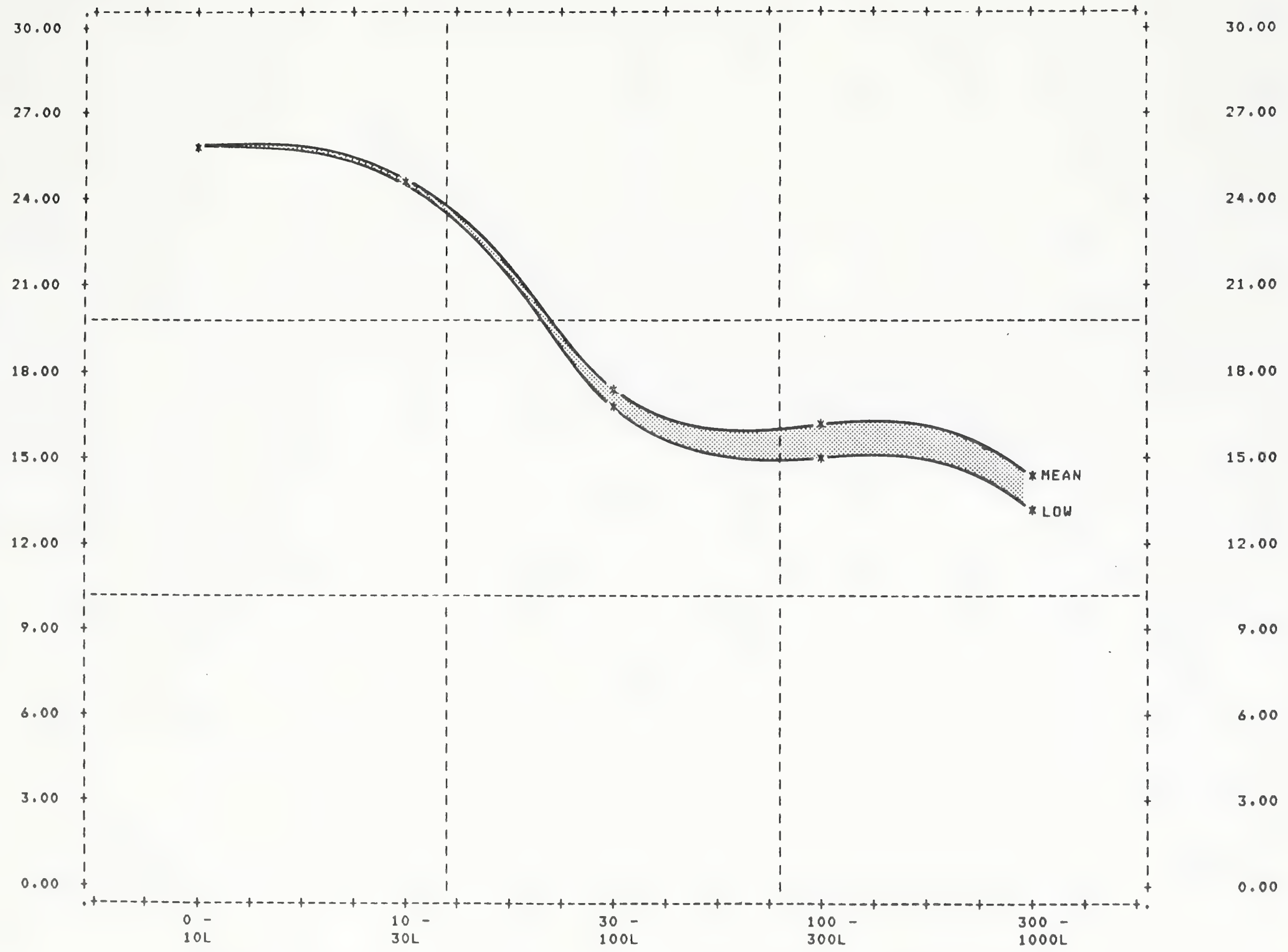


FIGURE 4.12 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L); SENSITIVITY TO DEFECTS

A second factor that has been identified in a substantial number of truck accidents is driver fatigue [51,54]. The long working day that is common in the trucking industry generally, has also been observed in Alberta and documented in an Alberta Environment study [42]. Statistical information indicates that fatigue may be responsible for 8% of the highway truck accidents, and 5% of the urban truck accidents. The contribution of driver fatigue to hazardous waste spills is indicated in Figure 4.13 which shows the transportation spill frequency estimates based on accident rates from which fatigue accidents have been removed. The corresponding volume reduction is 4%.

Finally, an attempt has been made here to evaluate the potential effects on spill rates that might result from driver training programs. Statistical information on the quantitative effect of training programs on accident rates is scarce, reflecting the difficulties inherent in such evaluation research. Accident rate reductions are difficult to measure accurately because of the great variability in individual accident rates, and the length of time over which observations must be taken to achieve stable measures. The data that are available, some of them relating specifically to truck drivers, and some to general driver training [18,24, 34,36,40,42,57] indicates that driver training has a type-specific effect on accident rate. Multi-vehicle collision accident rates seem to be reduced by driver training programs to a greater extent than the rates for other accident types. Based on the reductions quoted in the cited references, and on the location distribution of truck accidents [51], a 10% reduction of highway truck accident rates, and 15% reduction of urban rates is a reasonable estimate of the effect of driver training. Figure 4.14

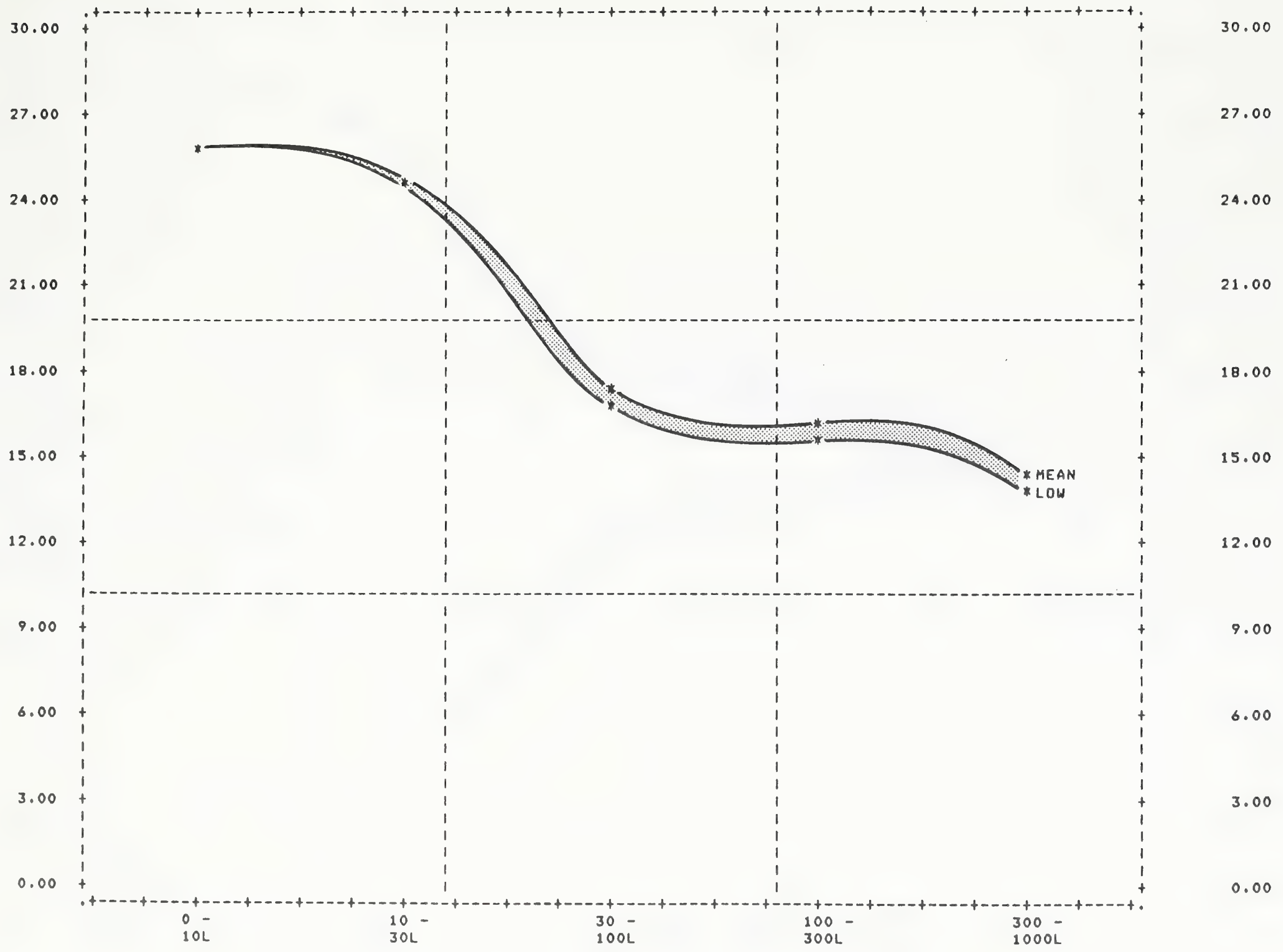


FIGURE 4.13 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILLS (L PER 1000 L); SENSITIVITY TO DRIVER FATIGUE

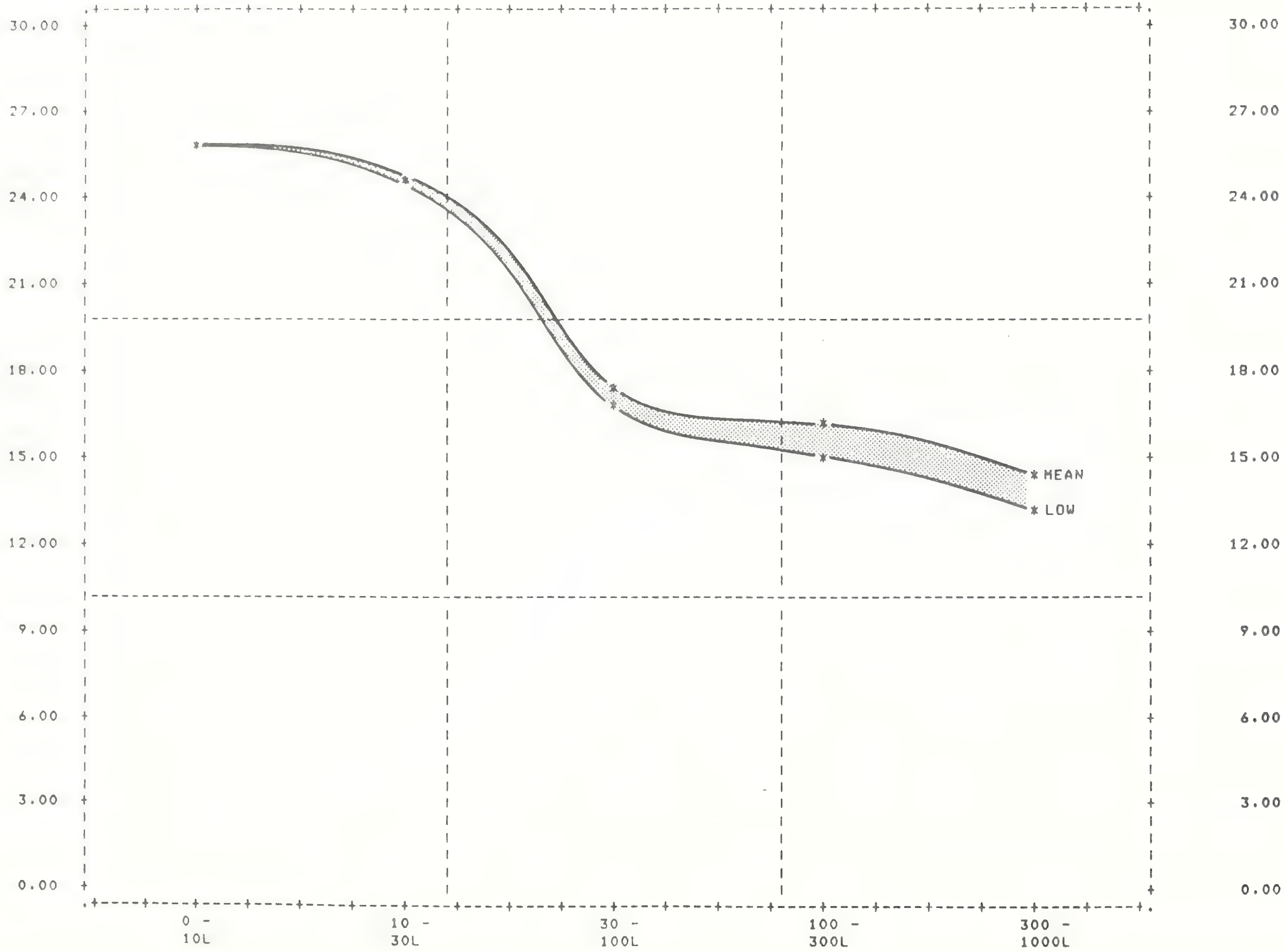


FIGURE 4.14 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON-FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILLS (L PER 1000 L); SENSITIVITY TO DRIVER TRAINING

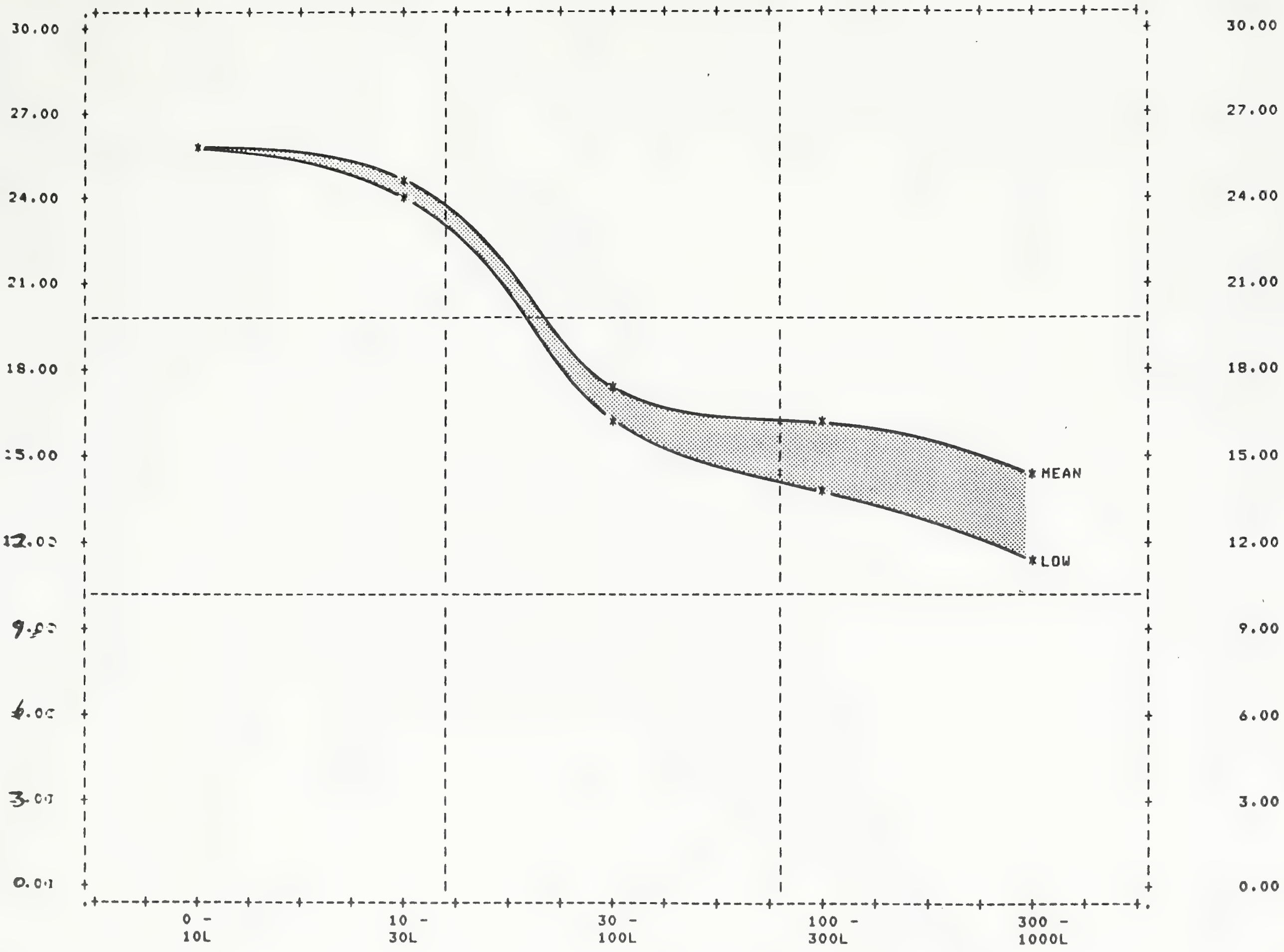


FIGURE 4.15 VACUUM TRUCK, 100 KM. MIXED ROUTE: NON FLAMMABLE CARGO SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L); SENSITIVITY TO DEFECT RATE, FATIGUE AND DRIVER TRAINING

shows the effects of these reductions on spill frequency estimates; the total expected transportation spill volume would drop by about 9%. Of course, whether this effect is achievable will depend on the proficiency of the driver population before training. Commercial truck drivers generally tend to be fairly good drivers[51] and this may limit the achievable benefits of training.

As an indication of the potential effects of a combined accident prevention program, the combined effects of the three factors were evaluated. Figure 4.15 shows the spill frequencies that result when the effects of eliminating vehicle defects and driver fatigue, and the estimated benefits of training, are all included in the calculations. The overall effect on predicted spill volume is a 20% reduction.

4.3.2 Loading and Unloading Sensitivity Analyses

Two sets of sensitivity analyses were performed for vacuum truck loading and unloading operations. In the first set, the input probabilities for basic events related to operator error and to equipment failures are varied from 50% to 150% of their original input values. Figures 4.16 to 4.19 show the corresponding effects on the spill volume estimates. It is apparent from the figures that the loading and unloading spill probabilities are more sensitive to operator errors than to equipment failure rates. It is also apparent that, on a proportional basis, the effects of factor variation are fairly evenly distributed over the range of spill sizes.

In a second set of sensitivity analyses the effects of cargo characteristics were evaluated. The assumptions used here regarding ignition probabilities and the effects of corrosion on equipment are the same assumptions that were used in the corresponding transportation

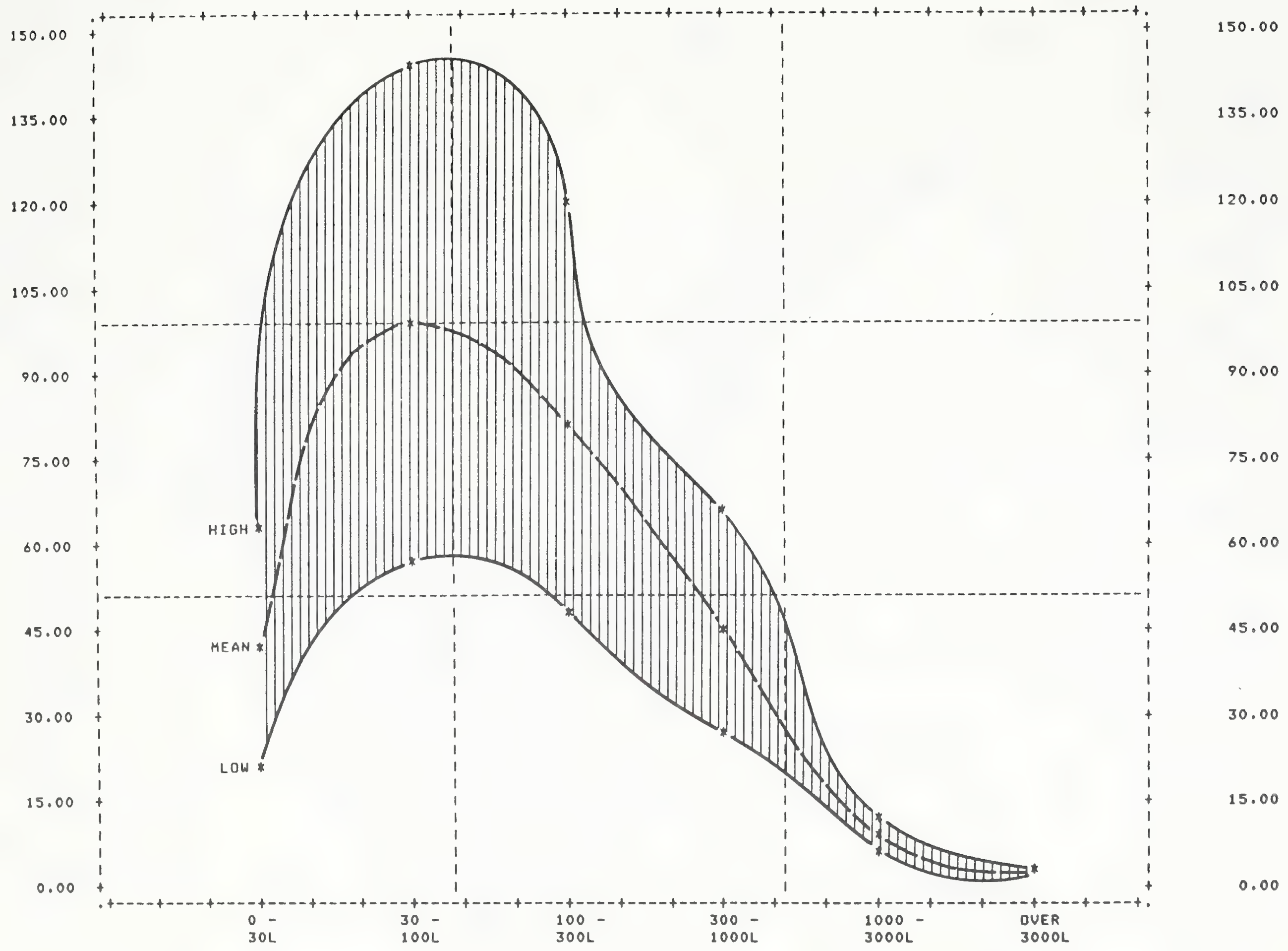


FIGURE 4.16 VACUUM TRUCK, LOADING, NON-FLAMMABLE CARGO: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL; SENSITIVITY TO OPERATOR ERRORS

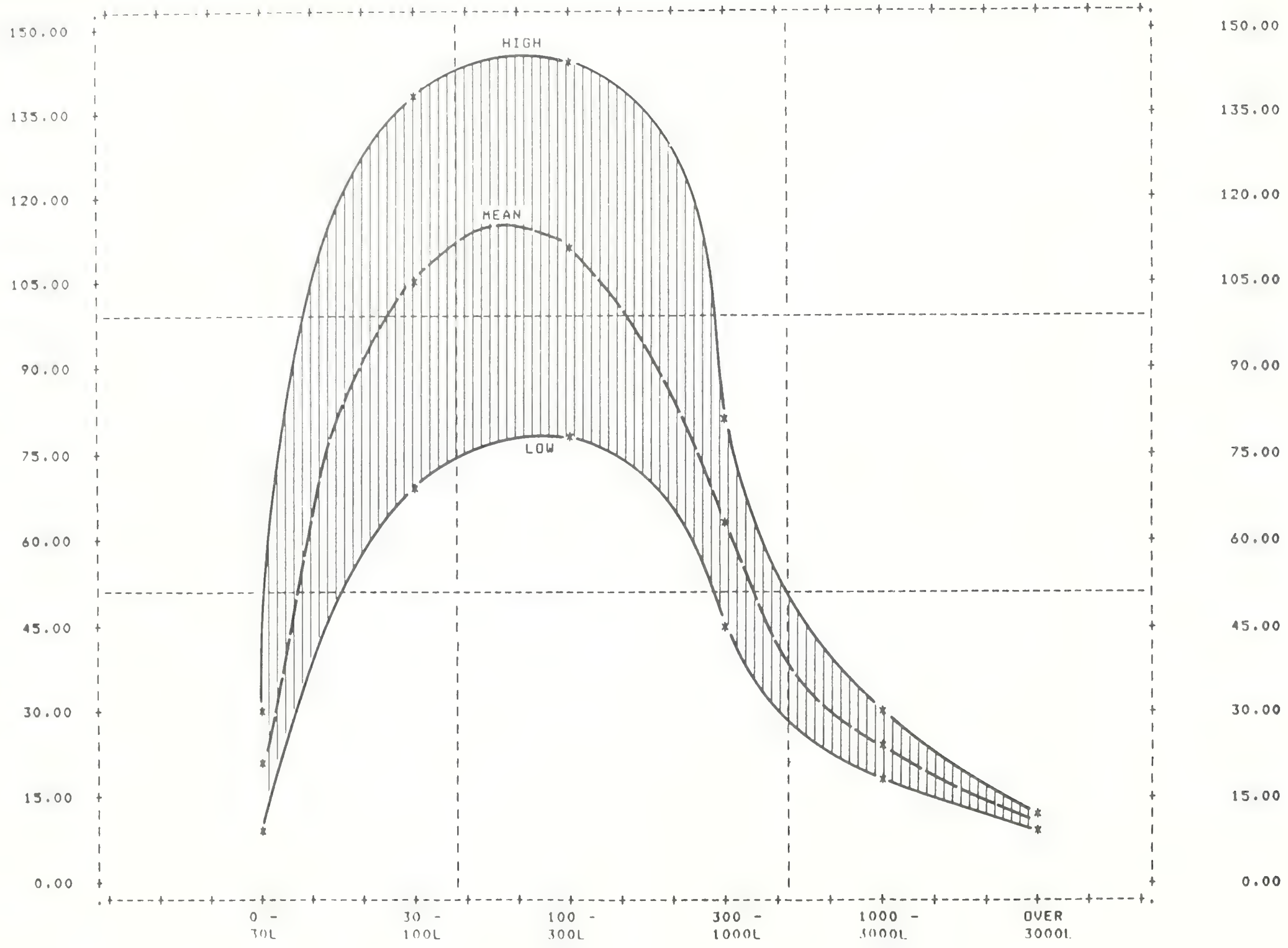


FIGURE 4.17 VACUUM TRUCK, UNLOADING, NON-FLAMMABLE CARGO: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL; SENSITIVITY TO OPERATOR ERRORS

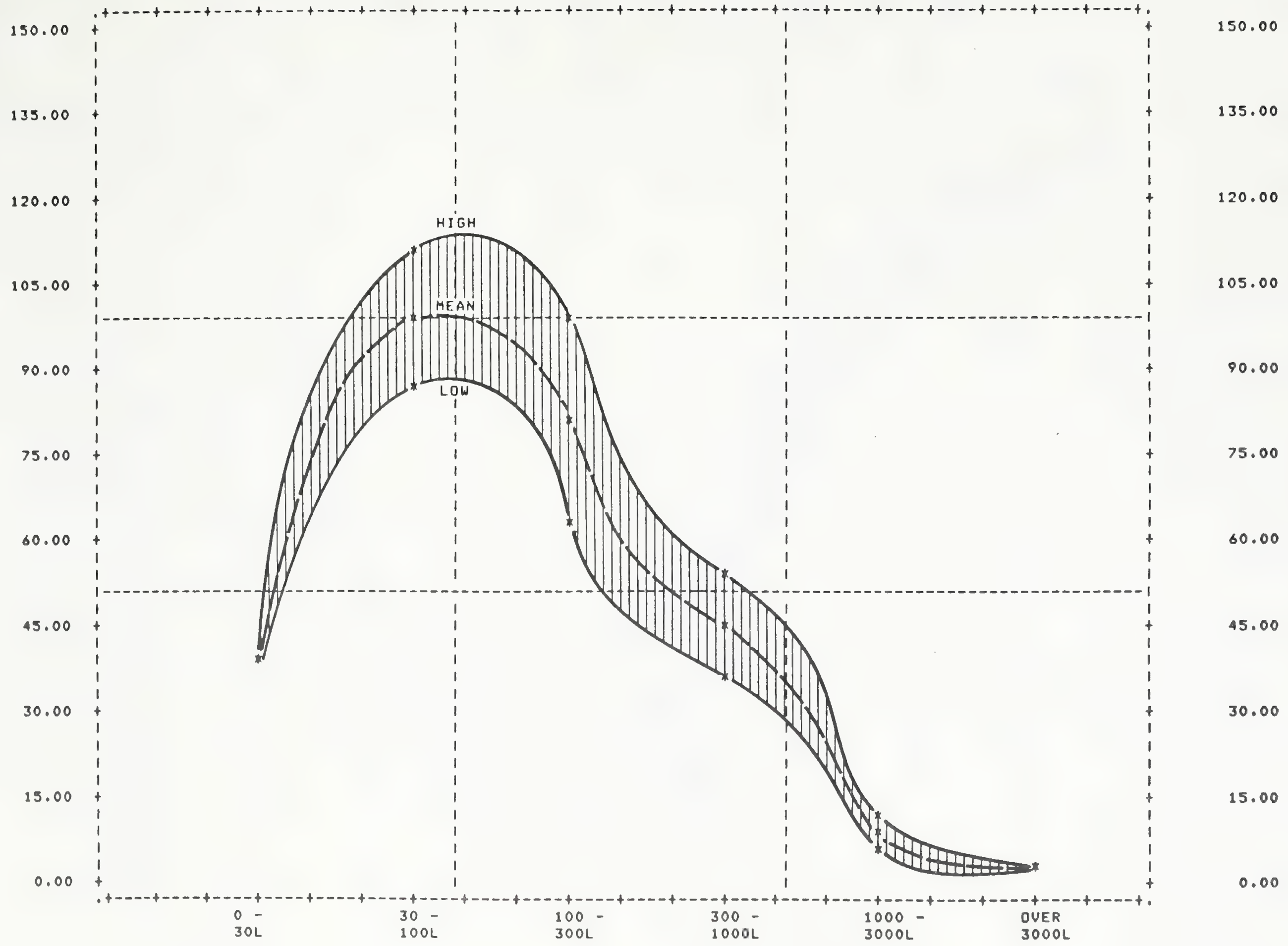


FIGURE 4.18 VACUUM TRUCK, LOADING, NON-FLAMMABLE CARGO: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL; SENSITIVITY TO EQUIPMENT FAILURE

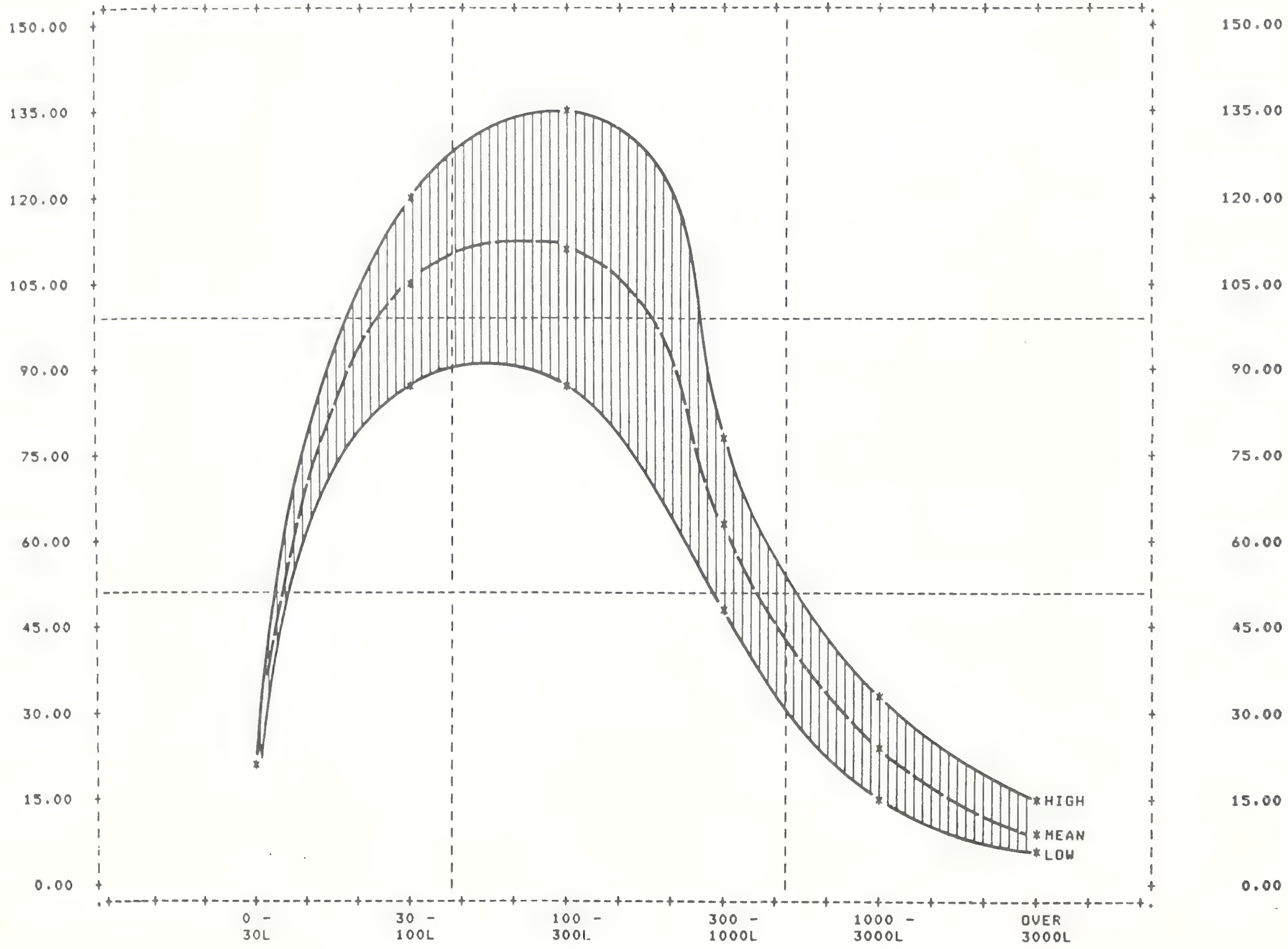


FIGURE 4.19 VACUUM TRUCK, UNLOADING, NON-FLAMMABLE CARGO: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL; SENSITIVITY TO EQUIPMENT FAILURE

sensitivity analyses. Because the probability is low that loading or unloading spills would ignite, the flammability of cargo has little effect on either spill frequencies or expected spill volumes. Fires would occur as a result of less than 1% of the larger loading and unloading spills.

Figure 4.20 shows the effect of corrosiveness on significant loading and unloading spill frequencies. The overall effect of corrosiveness is to increase loading and unloading release volumes by about 40%.

4.3.3 Review of Risk Factor Sensitivity Analyses

Tables 4.17 and 4.18 summarize the results of the analysis of transportation and transfer risk factors. The sensitivity analysis results in the two tables show the effect of variations in operator and equipment error rates on the predicted volume of waste spilled per million litres transported by vacuum truck. From Table 4.17 a 50% change in probability of human errors in the operation of the tanks ancillary equipment results in a change of 8% in the predicted volume spilled during transport. A 50% change in the probability of mechanical or material failures of this equipment results in a 20% change in volume spilled.

The sensitivity analysis results for transfer operations show a somewhat different pattern: a 50% change in operator or equipment error rates produces changes in the total volume of significant transfer spills of slightly more than 30%. The volume spilled in transfer operations is therefore more sensitive to these classes of error than the volume spilled during transportation, reflecting the greater complexity of the transfer procedures and physical systems, as well as the predominance of accident-caused cargo spills in the transportation volume.

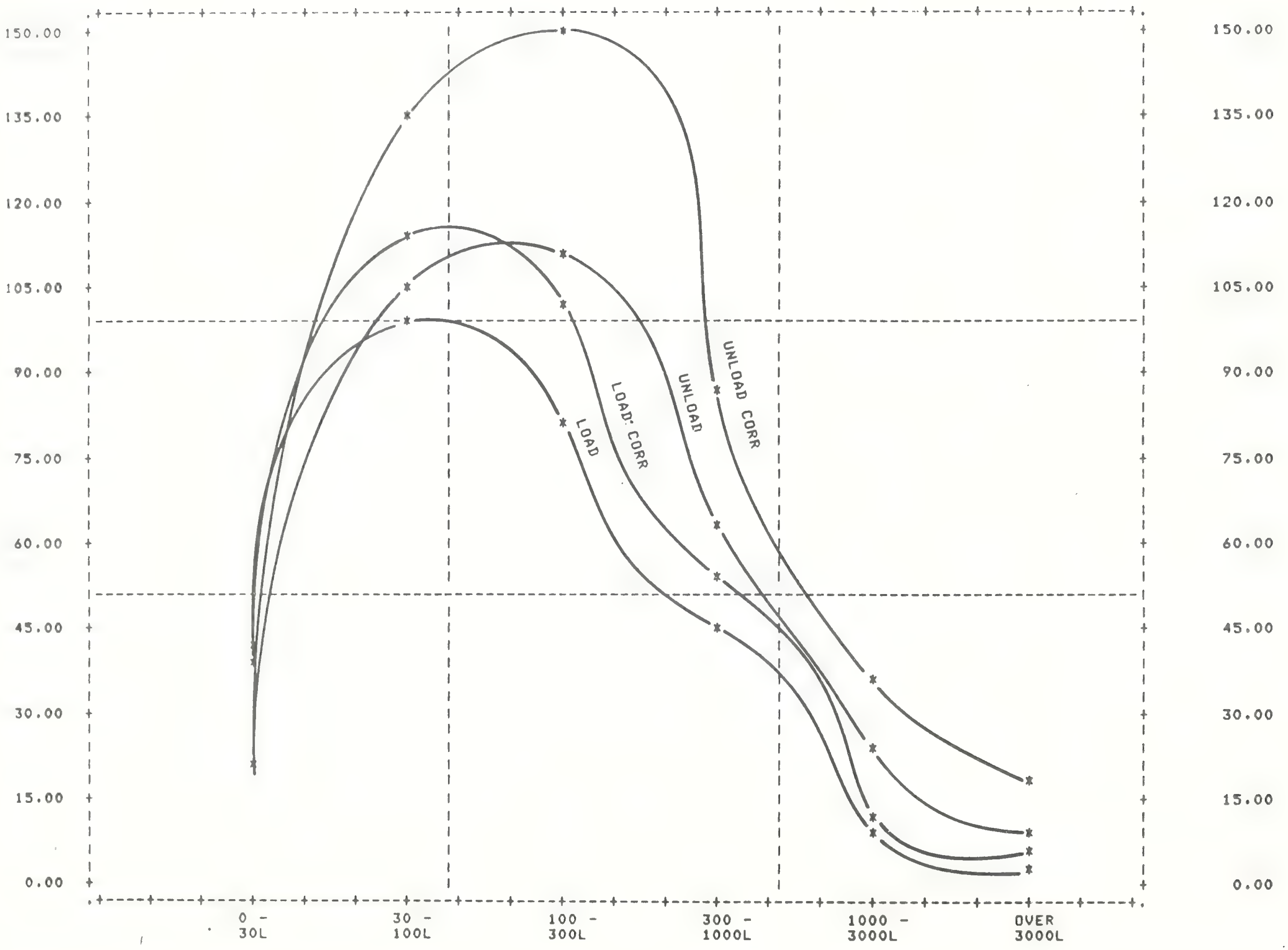


FIGURE 4.20 VACUUM TRUCK, LOADING AND UNLOADING, NON-FLAMMABLE CARGO: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL; SENSITIVITY TO CORROSIVE CARGO

TABLE 4.17

SENSITIVITY TO CHANGES IN OPERATOR AND EQUIPMENT ERRORS OF THE VOLUME SPILLED DURING TRANSPORT FROM A VACUUM TRUCK PER MILLION LITRES TRANSPORTED

	ERROR PROBABILITIES		
	0.5 X BASE	BASE CASE INPUTS	1.5 X BASE
OPERATOR ERROR	11.5	12.5	13.5
EQUIPMENT FAILURE	9.5	12.5	15.0

TABLE 4.18

SENSITIVITY TO CHANGES IN OPERATOR AND EQUIPMENT ERRORS OF THE VOLUME SPILLED DURING LOADING AND UNLOADING FROM A VACUUM TRUCK PER MILLION LITRES TRANSPORTED

	ERROR PROBABILITIES		
	0.5 X BASE	BASE CASE INPUTS	1.5 X BASE
OPERATOR ERROR	17.1	24.0	31.4
EQUIPMENT FAILURE	16.6	24.0	32.3

Tables 4.19 and 4.20 summarize the predicted effects of cargo characteristics on spill risk. For flammable cargoes, the probability of occurrence of fires, and volume of material involved, were evaluated by applying estimated ignition probabilities to the calculated spill probability. Although the occurrence of fire dramatically affects the consequences of an accident, fire has a small proportional effect on the total volume released, since it is most likely to occur in traffic accident spills, where a large proportion of the cargo will be released with or without a fire. The occurrence of fires is relatively infrequent in loading and unloading because ignition of the spilled material is infrequent under the controlled conditions of a transfer facility. The volume of flammable waste that is expected to burn is indicated in Tables 4.19 and 4.20.

Tables 4.19 and 4.20 show that cargo corrosiveness appears to have a substantial effect on both transportation and transfer spill volume, although these results should perhaps be regarded as showing maximum effects. The effects of corrosion on the probabilities of equipment failure were estimated from statistics relating to corrosive product, which may be more reactive than most corrosive waste.

The analysis of vehicle and driver factors is summarized in Table 4.21 . The estimated effects are derived from published estimates of the relative frequency of truck involvements in single and multiple vehicle accidents, and estimated of the effects of driver fatigue, training courses, and vehicle defects on the rates for each accident type. The results of the analysis indicate that a 20% overall reduction in spilled volume could result from driver training and the elimination, by scheduling and maintenance

TABLE 4.19

SENSITIVITY OF VOLUME SPILLED DURING VACUUM TRUCK TRANSPORT TO MODIFICATIONS OF INPUT PROBABILITIES CORRESPONDING TO CORROSIVENESS AND FLAMMABILITY OF CARGO

	BASE CASE INPUT	MODIFIED INPUT
CORROSIVENESS	12.5	15.0
FLAMMABILITY	12.5	12.6 (2.4)

( ) - VOLUME BURNED

TABLE 4.20

SENSITIVITY OF VOLUME SPILLED DURING VACUUM TRUCK LOADING AND UNLOADING TO MODIFICATIONS OF INPUT PROBABILITIES CORRESPONDING TO CORROSIVENESS AND FLAMMABILITY OF CARGO

	BASE CASE INPUT	MODIFIED INPUT
CORROSIVENESS	24.0	35.5
FLAMMABILITY	24.0	24.5 (0.2)

( ) - VOLUME BURNED

TABLE 4.21

SENSITIVITY OF VOLUME SPILLED DURING VACUUM TRUCK TRANSPORT TO MODIFICATIONS OF ACCIDENT RATES CORRESPONDING TO TRAINING AND MAINTENANCE EFFECTS, AND ELIMINATION OF FATIGUE

	BASE CASE AR	MODIFIED AR
FATIGUE	12.5	12.0
TRAINING	12.5	11.5
MAINTENANCE	12.5	11.5

programs, of driver fatigue and vehicle defects, with fatigue effects contributing 4%, and training and maintenance contributing about 8% each.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

This study has examined the operations of loading, transport, and unloading that are involved in the transportation of hazardous waste materials in a tank truck. From interviews with operating personnel, and analysis of operating procedures and facilities for each of the three component operations, fault trees were developed that portray the credible accident sequences by which hazardous wastes could be released. Probabilistic inputs were generated for the basic events of the fault trees, and estimates were calculated for the expected frequencies of release incidents and expected release volumes. Although the values of these estimates depend on a great many assumptions and must be regarded as approximations, they provide a reasonable guide to the relative magnitudes of the risks in the various components of the overall operation.

Two sets of analyses were conducted:

(a) A basic risk analysis including the estimation of spill risks in transportation, loading, and unloading with particular attention being given to route and tank truck characteristics.

(b) An investigation, using sensitivity analysis methods, of the contribution to spill risk of operator error, equipment failure, cargo characteristics, and training and maintenance.

The results of the basic analysis showed the relationships between a number of truck and route characteristics and overall levels of risk:

(a) Because accidents on urban streets tend to be much less severe than accidents on primary highways, the probability of a cargo spill in an urban traffic accident is much lower per vehicle kilometer than in a highway accident.

(b) A vacuum truck with a 10,000 litre tank will operate with about the same probability of cargo spills per vehicle kilometer as a 20,000 litre tractor-tank trailer unit. (About 30 accident-caused, and 60 non-accident spills would be expected per million trips on a 100 km. route consisting of 80 km. of primary highway, 15 km. of urban arterial, and 5 km. of secondary road, all with average accident rates). Thus, the expected number of cargo spills per million litres transported is twice as large for a vacuum truck as for a tractor trailer unit; however, since the volume released in a cargo spill tends to be proportional to tank capacity, the total volume spilled will be roughly equal. (For the average 100 km. route, 12.6 and 10.5 litres per million litres, for vacuum trucks and tank trailers respectively).

(c) Spills during loading and unloading operations will account for most of the waste released during transport and handling. Per million litres transported, about 460 litres would be expected to spill during loading and unloading operations for a vacuum truck, and about 240 litres for a tractor trailer, the difference between the two truck types again reflecting the difference in the number of trips required to transport one million litres.

(d) The consequences of a spill occurrence, of course, depend largely on its size. For vacuum trucks, about 30 loading, transportation, or unloading spills larger than 3,000 litres would occur in one million trips; about 50 such spills would be expected for tank trailers. On the basis of volume spilled per million litres transported, the truck types are more equal. For both types of truck, about 8 litres would be expected to be lost in large spills, per one million litres transported. When these spills larger than 3,000 litres are considered separately, transportation incidents appear to account for about 50% of the spills, the remainder occurring during loading and unloading.

In the second set of analyses that were conducted, the sensitivity analyses, operator error effects were shown to be a substantial component in loading and unloading spill risk--a 50% change in the operator error rate translated into a 30% change in the expected volume spilled in cargo releases. Equipment failure rates were also a major component, reflecting the complex systems and procedures involved in loading and unloading operations. Transportation risk is largely determined by route and vehicle characteristics, but tank and ancillary equipment failures were found to have a substantial effect on transport spill risk--a 50% failure rate change translated into a 20% spill volume change--and (non-driving) operator errors had a slight effect.

Flammability and corrosiveness were the two primary cargo characteristics of interest. Flammability of cargo has little effect on the expected volume of waste spilled, but does of course effect the consequences of spills. Fires were fairly probable in transportation spills of flammable cargo (about 25% of traffic accident spills would ignite) but relatively unlikely in other spill accidents. Corrosiveness of the cargo appears to have a potentially large effect on spill risks, increasing expected volumes spilled by as much as 25% in transport and 40% in handling. Finally, the effects on transportation risk of driver fatigue, driver training, and vehicle defects were investigated. When accident rates were reduced by the elimination of accidents due to driver fatigue and vehicle defects, and of avoidable accidents that would be prevented by training, the expected volume of waste spillage in transportation was reduced by 20%.

5.2 Recommendations

Consideration of the common accident types predicted by the present study, and of the relationship between the probability of their occurrence and the various risk factors, leads to several fairly specific recommendations as to the errors which should be emphasized in the attempt to reduce the probability of accidental waste releases:

(a) A complete drainage control system is essential at the truck loading and unloading sites--most of the liquid waste spills will occur during transfer operations, and drainage collection and disposal systems would almost completely control this major source of waste releases.

(b) Because the probability of spills at the truck loading and unloading sites has a strong operator component, the volume of spilled waste would be substantially reduced by the careful training of operators and well defined procedures for truck loading and unloading, and the provision of automatic overflow prevention devices. The operator training should emphasize the dangers inherent in spills, the risk of spills at various points in the operating procedures, and the importance of monitoring on-going operations to minimize the likelihood of undetected leaks and spills.

(c) Since route characteristics--accident rate, length, and accident severity--are the major determinants of transportation spill risks, routes should be carefully selected whenever alternatives are available, in order to minimize the probability of cargo spill accidents.

(d) Because equipment failure rates have a substantial effect on the probability of spills in all three operations, the careful inspection and frequent maintenance of fittings, gaskets, pumps, and other equipment should be prescribed for all mechanical components of the waste transport system.

(e) Because of the potential consequences of any fire involving the storage tank or tanker trucks at transfer sites that handle flammable cargo, the establishment of fire control procedures and the availability of fire fighting equipment must be given the highest priority at these sites.

(f) Transfer sites should be well protected from vandalism or sabotage.

(g) For the transport of flammable waste cargoes, the relatively high probability of cargo fire in a traffic accident, and the severe consequences of a cargo fire, justify the provision of fire suppression systems on tank trucks transporting flammable waste cargo.

(h) Several other transportation risk factors should be considered in formulating regulations or guidelines to waste transportation: results of this analysis indicate that a carefully planned and monitored vehicle maintenance program, training of drivers in defensive driving and collision avoidance principles, and the restriction of fatiguing work schedules, would substantially reduce the frequency of cargo spills during transport.

(i) Corrosive cargo appears to require special care in handling and transport. Any procedure, such as tank washing, that will control corrosion damage to equipment should be implemented, as it would have a substantial effect on spill probabilities. Restrictions should also be placed on the vehicles that may be used for the transport of corrosive wastes, to ensure that all tanks and fittings are corrosion-resistant.

(j) Although the choice of vehicle type will be determined primarily by cargo volume, and by the availability of tank loading facilities at the waste generating site, some consideration should be given to risk reduction when a choice of vehicle is possible. A larger tank trailer unit would be preferable to a vacuum truck for the transport of a large volume of waste because of lower accident exposure and expected accident costs per million litres transported. The size disadvantage of the vacuum truck could be overcome by reducing the spill rate per vehicle kilometer. The present analysis suggests that this could be accomplished if vacuum truck valves and fittings were as secure and protected as they are on many tank trailers; this should be considered in the formulation of specifications for hazardous waste transport vehicles.

The implementation of these recommendations would not, of course, eliminate all hazardous waste releases, but would ensure that preventive effort are directed towards the major sources of risk in the transportation and handling of wastes.

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APPENDIX A

ANALYSIS OF TWO ALTERNATIVE TRANSPORTATION ROUTES

ANALYSIS OF TWO ALTERNATIVE TRANSPORTATION ROUTES

In order to demonstrate the application of the methods developed in the study, estimates of the frequency in volume of spills were calculated for the transportation of liquid waste in vacuum trucks along two alternative primary highway transport routes between Calgary and Edmonton: Highway 2, and Highways 21, 1, and 14. The two routes differ with respect to both length and estimated spill rate per million vehicle kilometers. The route consisting of segments of Highways 21, 1, and 14 is longer than the Highway 2 route, and also has a higher accident rate. The effects are clearly indicated in the results presented in Figures A.1 and Tables A.1 and A.2, which show that the frequency and expected volume of cargo spills are considerably lower on the Highway 2 route.

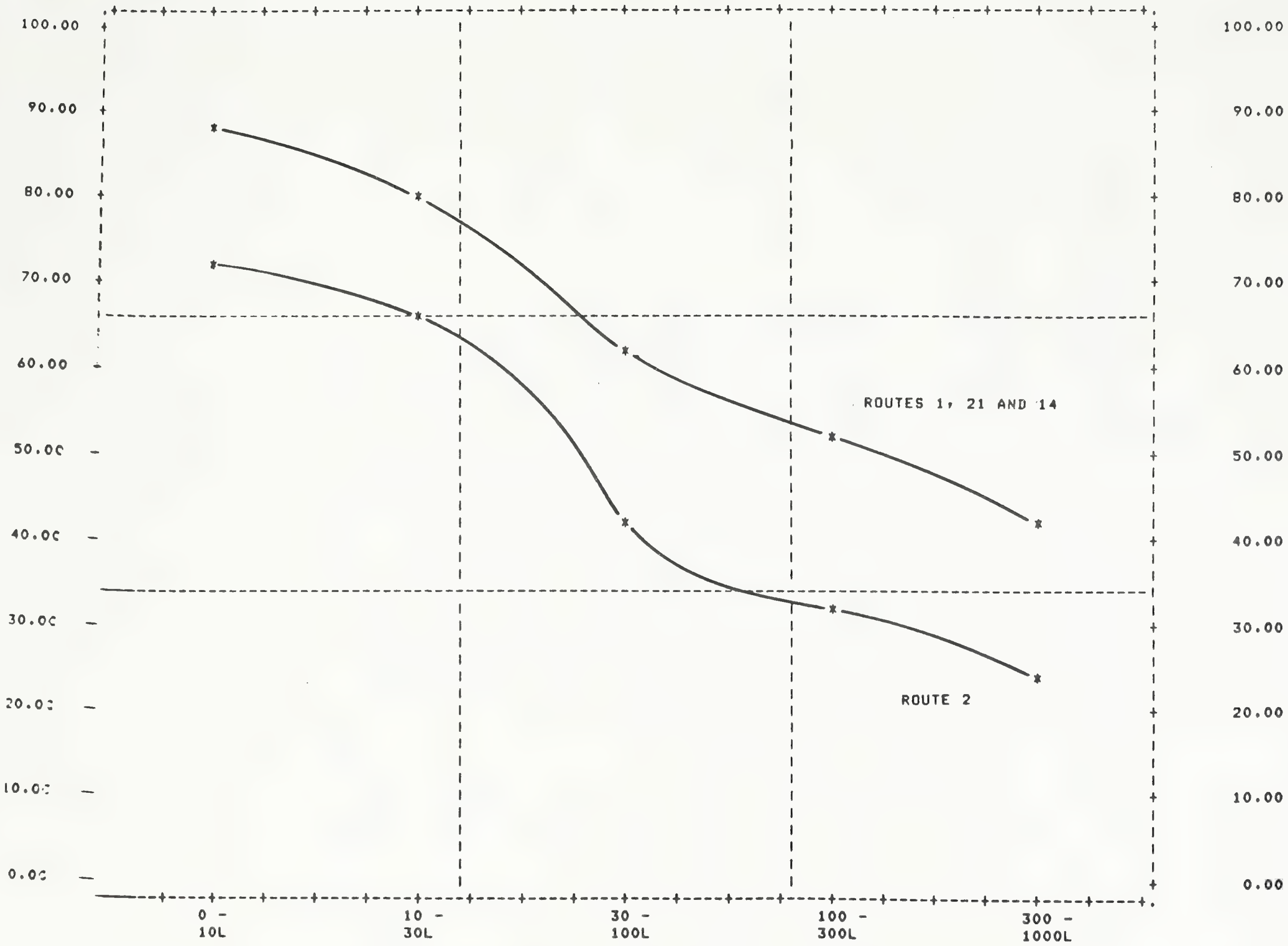


FIGURE A.1 VACUUM TRUCK, CALGARY TO EDMONTON: FREQUENCY OF SPILLS PER 1,000,000 TRIPS VERSUS VOLUME OF SPILL (L PER 1000 L) VIA HIGHWAY 2 AND HIGHWAYS 1, 21, and 14

TABLE A.1

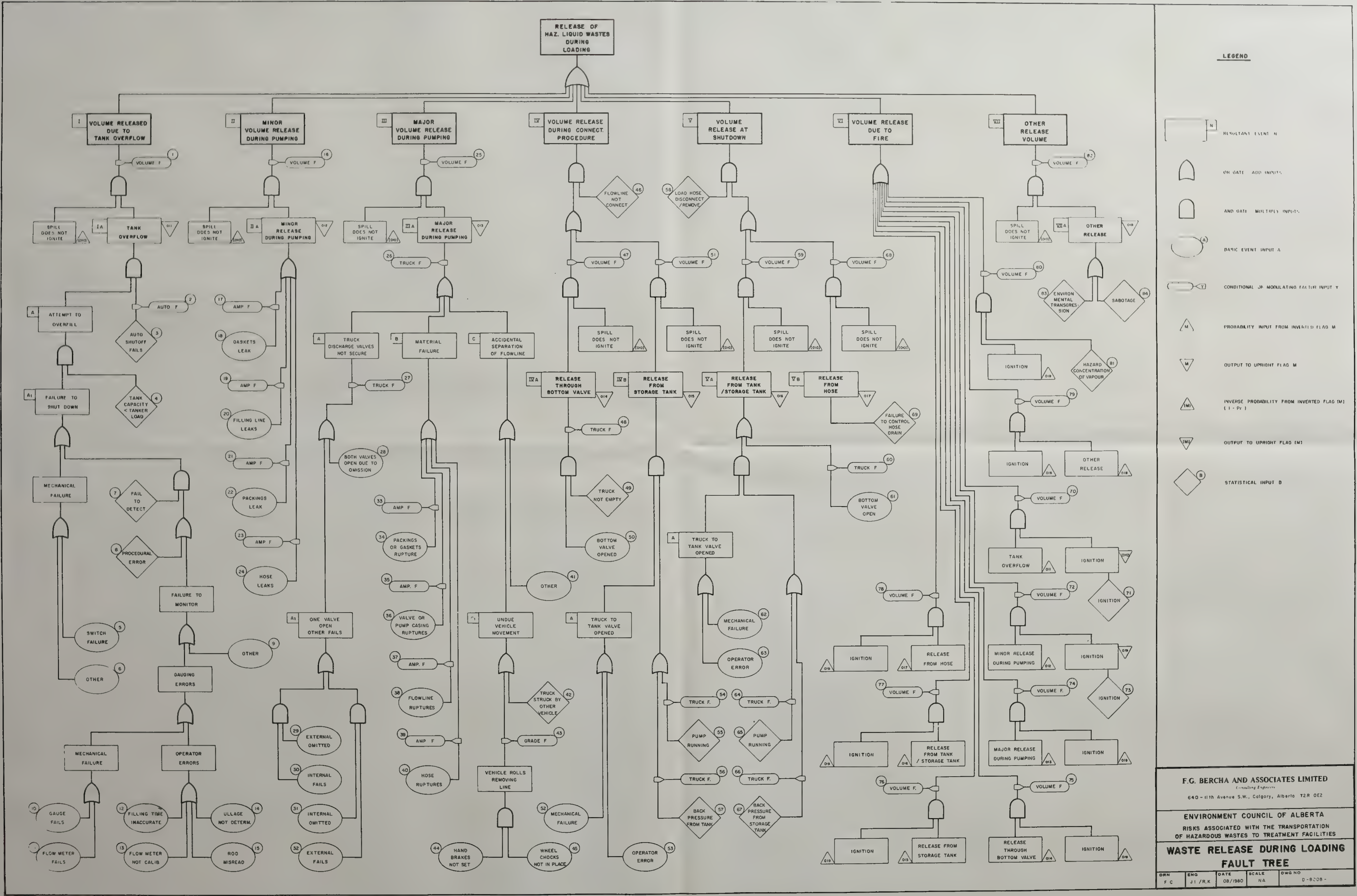
NUMBER OF SPILLS PER MILLION VACUUM TRUCK TRIPS ON ALTERNATE CALGARY - EDMONTON ROUTES

	HIGHWAY 2	HIGHWAYS 1, 21 & 14
UNDER 10L	71.65	87.50
10L - 30L	65.94	79.51
30L - 100L	41.75	61.01
100L - 300L	31.67	51.76
300L - 1000L	23.28	42.43
COLUMN TOTAL	46.86	64.44

TABLE A.2

VOLUME OF CARGO SPILLED PER MILLION LITRES TRANSPORTED BY VACUUM TRUCK ON ALTERNATE CALGARY - EDMONTON ROUTES

	HIGHWAY 2	HIGHWAYS 1, 21 & 14
UNDER 10L	0.02	0.03
10L - 30L	0.12	0.14
30L - 100L	0.23	0.34
100L - 300L	0.57	0.93
300L - 1000L	1.30	2.38
COLUMN TOTAL	2.25	3.80



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OF HAZARDOUS WASTES TO TREATMENT FACILITIES

WASTE RELEASE DURING LOADING
FAULT TREE

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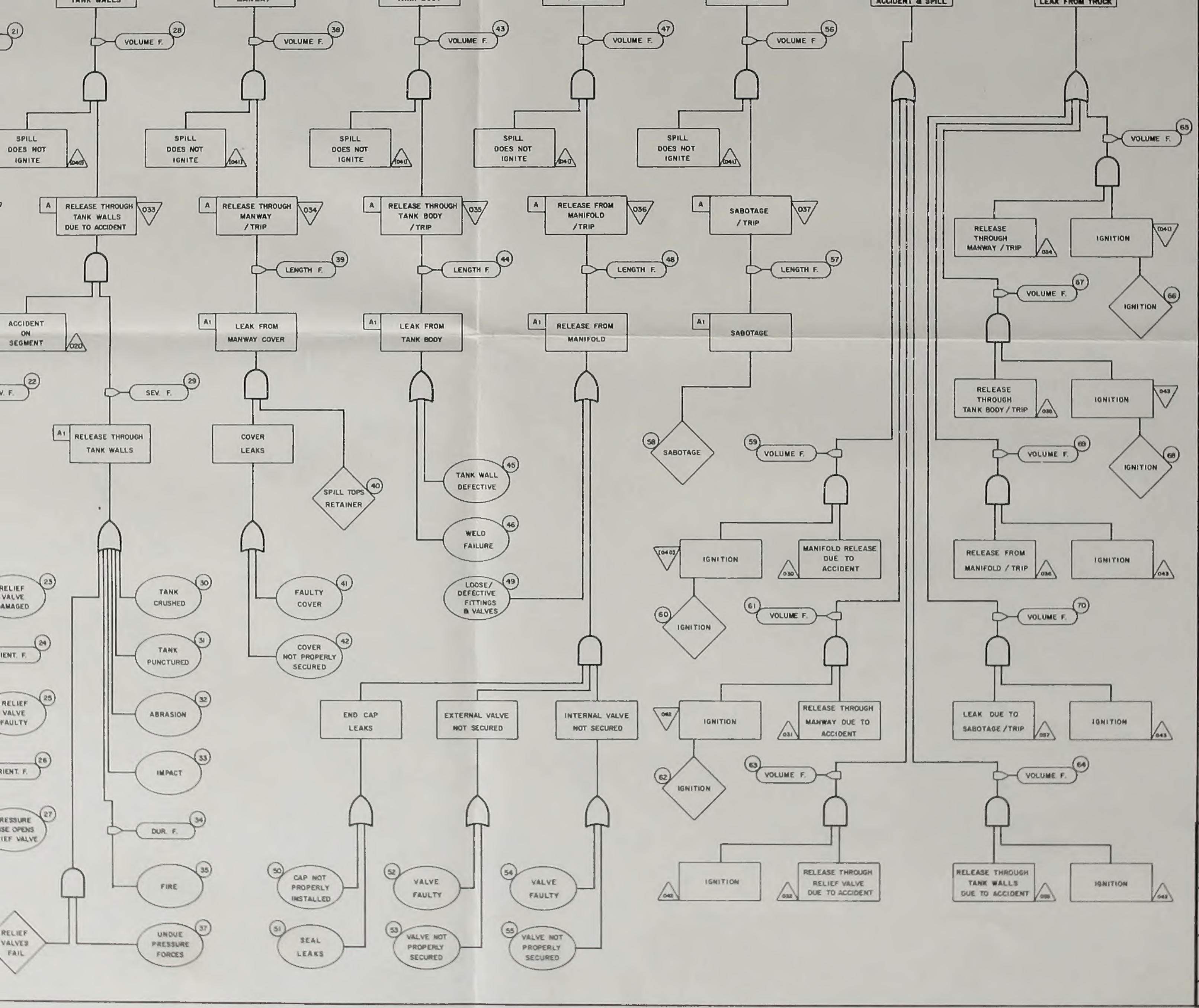

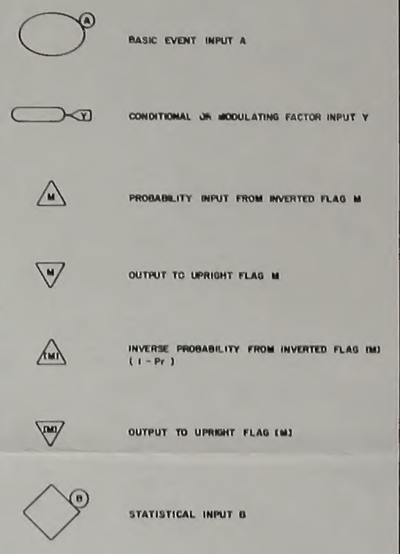
A
BASIC EVENT INPUT A
Y
CONDITIONAL OR MODULATING FACTOR INPUT Y
M
PROBABILITY INPUT FROM INVERTED FLAG M
M
OUTPUT TO UPRIGHT FLAG M
(M)
INVERSE PROBABILITY FROM INVERTED FLAG (M) (1 - Pr)
(M)
OUTPUT TO UPRIGHT FLAG (M)
B
STATISTICAL INPUT B

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WASTE RELEASE DURING TRANSPORTATION FAULT TREE

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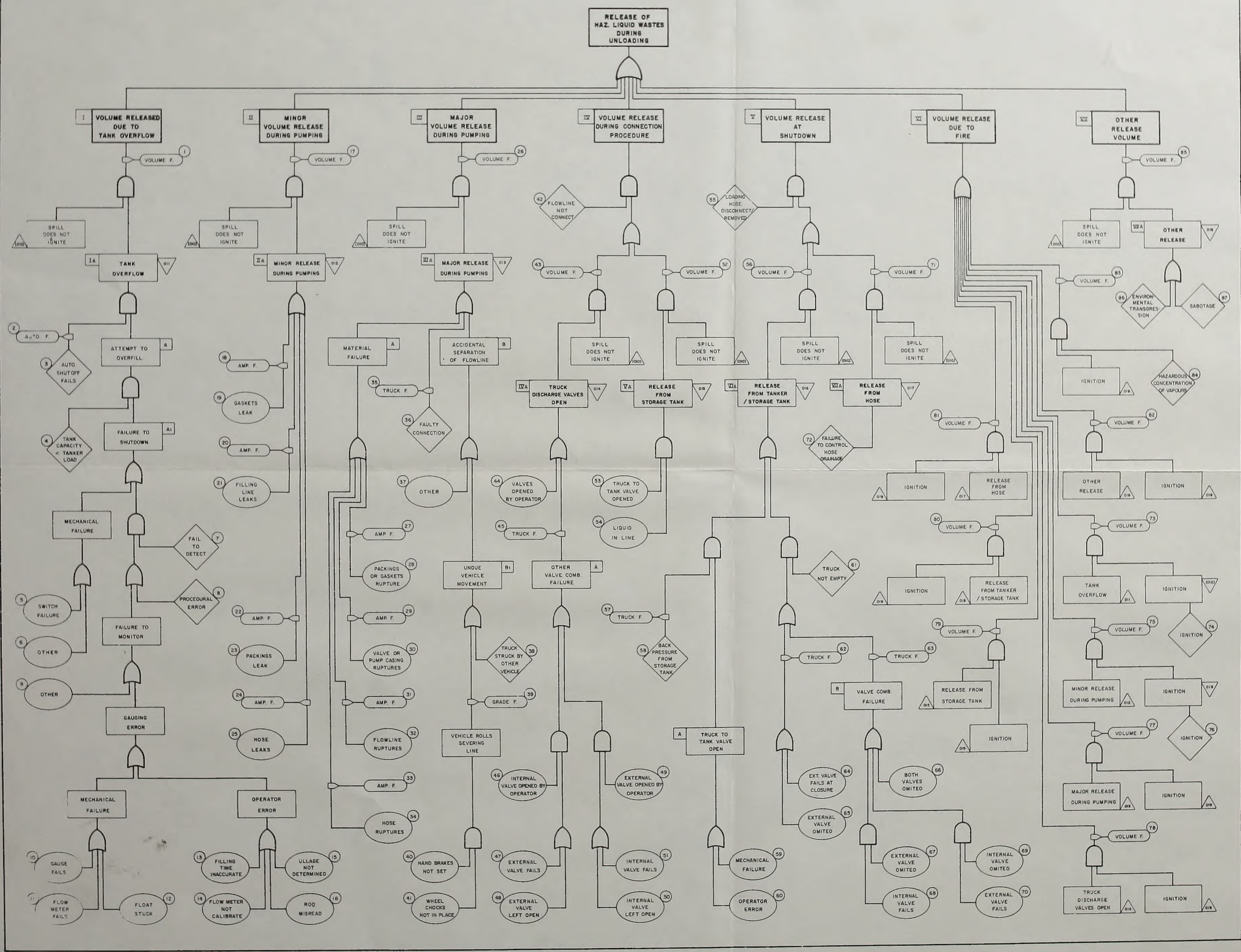

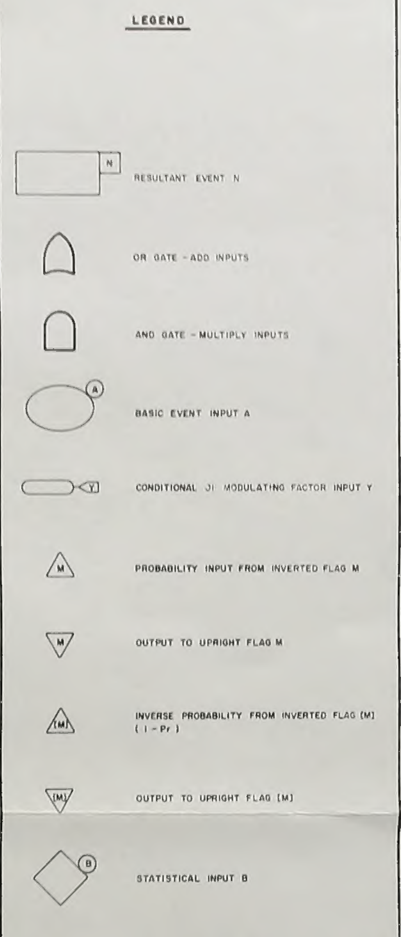
LEGEND
N RESULTANT EVENT N
OR GATE - ADD INPUTS
AND GATE - MULTIPLY INPUTS
A BASIC EVENT INPUT A
Y CONDITIONAL (Y) MODULATING FACTOR INPUT Y
M PROBABILITY INPUT FROM INVERTED FLAG M
M OUTPUT TO UPRIGHT FLAG M
[M] INVERSE PROBABILITY FROM INVERTED FLAG [M] (1 - Pr)
[M] OUTPUT TO UPRIGHT FLAG [M]
B STATISTICAL INPUT B

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WASTE RELEASE DURING UNLOADING FAULT TREE

DRN.	ENG.	DATE	SCALE	DWG.NO.
F.C.	J.I./R.K.	08/1980	NA	D-8008-3

N.L.C. - B.N.C.
3 3286 12472557 9